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HIGHLIGHTS

Small et al., Antarctic ice sheet palaeo-thinning rates from vertical transects of cosmogenic exposure ages.

- Exposure ages that constrain ice sheet thickness collated from an online database.
- Thinning rates are reconstructed from 23 sites across Antarctica.
- Palaeo-thinning rates are comparable to modern observations.
- Wide-spread thinning during the Holocene, but after Meltwater Pulse 1A.

Antarctic ice sheet palaeo-thinning rates from vertical transects of cosmogenic exposure ages.

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Abstract

Constraining Antarctic ice sheet evolution provides a way to validate numerical ice sheet models that aid predictions of sea-level rise. In this paper we collate cosmogenic exposure ages from exposed nunataks in Antarctica that have been used, or have the potential to be used, to constrain rates of thinning of the Antarctic Ice Sheets since the Last Glacial Maximum. We undertake quality control of the data and adopt a Bayesian approach to outlier detection. Past thinning rates are modelled by Monte Carlo linear regression analysis. We present thinning rates from 23 sites across Antarctica. The resulting data set is the first Antarctic-wide collation of past ice sheet thinning rates and provides an empirical starting point for future model-data comparisons. Palaeo-thinning rates are spatially variable with high rates appearing to correlate to areas of contemporary rapid changes. On centennial timescales past thinning rates are comparable to modern day observations implying that modern day thinning has the potential to persist for centuries in numerous parts of Antarctica. The onset of abrupt thinning from all sites post-dates Meltwater Pulse 1A suggesting that its source region(s) are distal to areas where exposure age constraints on ice surface geometry exist.

Keywords: Holocene; Glaciology; Antarctica; Cosmogenic isotopes; Ice sheet thinning; Model-data comparison.

36 1. Introduction

37 Anthropogenic climate change is driving changes in the Antarctic Ice Sheets (AISs) which will be
38 the largest contributors to future sea-level rise (IPCC, 2013). Present day measurements indicate
39 that Antarctica is losing mass (Shepherd et al., 2012) and the rate of mass loss is increasing
40 (Rignot et al., 2011; Velicogna et al., 2014; Harig and Simons, 2015; Shepherd et al., 2018). Most
41 observed mass loss occurs as rapid changes to the major ice streams that drain the AISs
42 (Shepherd et al., 2001; Pritchard et al., 2009; Flament et al., 2012; Joughin et al., 2014; Rignot et
43 al., 2014; Scheuchl et al., 2016; Konrad et al., 2018). Modern observations can directly constrain
44 the timing and rates of ice mass changes in Antarctica (Miles et al., 2013; Rignot et al., 2014;
45 Konrad et al., 2018) and help identify the mechanisms that drive mass loss (De Angelis and
46 Skvarca, 2003; Pritchard et al., 2012). However, they are limited to the last ~60 years for which
47 satellite and direct observations exist, preventing modern rates being placed in a longer-term
48 context. Palaeo-data can contextualise modern-day observations and provide a longer temporal
49 record of the behaviour of the AISs (e.g. Bentley, 2010; Balco, 2011; Stokes et al., 2015).

50 In recent years surface exposure dating (SED) using *in situ* terrestrial cosmogenic nuclides has
51 contributed greatly to an improved understanding of the evolution of the AISs since the Last
52 Glacial Maximum (LGM) (e.g. Ackert et al., 1999; Stone et al., 2003; Bentley et al., 2006;
53 Mackintosh et al., 2007; Johnson et al., 2014; Balco et al., 2016). Given the general scarcity of
54 ice-free areas and the fact that much of the ice sheet margin is marine based, studies that use
55 SED to constrain the former lateral extent of ice are rare (cf. Joy et al., 2017). A more common
56 approach involves dating erratic cobbles – glacially-transported rocks that have been deposited
57 on nunataks as the ice sheet thinned – to constrain vertical changes in the AISs from the LGM to
58 the present day: the so-called ‘dipstick approach’ (e.g. Ackert et al., 1999; Stone et al., 2003).

59 As an ice sheet thins, and assuming no prior exposure, cosmogenic exposure ages of erratic
60 cobbles deposited on nunataks will get progressively younger as elevation decreases. This
61 principle allows the past surface geometry of the ice sheet to be constrained by: 1) providing
62 minimum constraints on the extent and timing of the maximum ice sheet surface elevation where
63 a sample is from below said maximum, and 2) directly constraining past ice surface elevation
64 (and timing) where the sample is from a setting that delimits the former ice sheet surface.
65 Similarly, where samples are from progressively lower altitudes they provide an opportunity to
66 constrain surface elevation change through time (Figure 1). Over relatively short time-scales (e.g.
67 $\sim 10^2 - 10^5$ years) this ice surface elevation broadly defines ice thickness, given knowledge of bed
68 elevation. An increasing number of studies have presented SED ages from vertical transects and
69 some have used these data to reconstruct past rates of thinning. Thinning histories have been
70 linearly extrapolated from cosmogenic exposure ages (e.g. Johnson et al., 2008; Bentley et al.,
71 2010) and modelled using Monte Carlo (MC) linear regression analysis (e.g. Johnson et al., 2014;
72 Jones et al., 2015; Hein et al., 2016).

Reconstructed thinning rates are important because they: 1) offer a dataset that can be used to assess the output of numerical ice sheet models, and 2) inform on processes that influence deglacial behaviour but are not currently operating or operate on timescales beyond the observational record. In this paper we present a dataset of reconstructed thinning rates, calculated from a collation of cosmogenic exposure ages from Antarctica that will be used in a future model-data comparison exercise. We use a consistent approach to quality control and calculation of thinning rates to allow direct comparison between the reconstructed rates. Our compilation of palaeo-thinning rates is compared to contemporary changes in the ice sheet to inform on potential drivers of past thinning. Finally, our approach allows us to place temporal constraints on thinning and we compare these to global sea-level change since the LGM.

2. The utility of thinning rates for model-data comparison

Geological observations can be used to test the hindcasting abilities of numerical ice sheet models and improve future estimates of sea-level rise (Tarasov et al., 2012; Whitehouse et al., 2012; Briggs and Tarasov, 2013; Lecavalier et al., 2014; Stokes et al., 2015). Traditionally, workers have compared ice sheet model outputs to point measurements that constrain ice sheet configuration at some time in the past (e.g. Briggs et al. 2014; Ely et al., *in review*). Undertaking such model-data comparisons requires a quantification of uncertainties associated with both ice sheet models and geological data (cf. Briggs and Tarasov, 2013). Models use simplifications of real-world physical processes to reconstruct ice sheet configuration and evolution in time. A modelled deglaciation chronology is the product of boundary conditions (e.g. basal sliding, bed topography, climate-ocean forcing, grid-resolution) imposed on that particular experiment; by adjusting parameters, model ensembles can explore the parameter space and quantify (to some degree) uncertainties on modelled deglaciation chronologies (Tarasov and Peltier, 2004; Briggs et al., 2014). Similarly geological data have uncertainties in both measurement and interpretation. These can be quantified through appropriate data reduction and laboratory procedures (e.g. Rood et al., 2013; Corbett et al., 2016) or through expert judgement (e.g. Hughes et al., 2016). However, geological processes introduce an implicit and often unquantifiable level of uncertainty. This can stem from i) factors that could affect the measured property prior to sampling, which workers have little control over, and ii) the strength of the geological association between the material that is being dated and the event of interest. This ‘geological uncertainty’ (cf. Small et al., 2017) requires that geochronological data undergo some form of quality control before further use (Blockley et al., 2008; Graf, 2009; Small et al., 2017).

In continental-scale model-data comparisons the spatial distribution and contiguity of geological data is fundamentally different to ice sheet model output (Ely et al., *in review*). Ice sheet models produce spatially and temporally continuous outputs for the model domain, albeit at a defined spatial (grid cell) and temporal (time-step) resolution. Conversely geological data usually

110 represent point measurements in space and time that, providing the data point is accurate,
111 constrain ice sheet configuration (e.g. ice free vs. ice covered). The disparity in scale requires
112 point data constraints be assumed to represent the configuration of the ice sheet for the entirety
113 of the grid cell to which the data have been assigned. This may be unrealistic when many
114 ‘dipstick’ measurements occur in regions of complex topography, rather than a smooth ice sheet
115 surface. One approach to bridge this gap is to spatio-temporally interpolate geological data. For
116 lateral ice sheet margins this can be done by creating isochrones of ice margin positions (Clark et
117 al., 2012; Bentley et al., 2014; Hughes et al., 2016) or through a Bayesian approach to modelling
118 geochronological data that produces deglacial ages and age uncertainties along a reconstructed
119 flowline (Chiverrell et al., 2013; Small et al., 2018). For changes in ice sheet surface elevation,
120 vertical transects of geochronological data provide constraints on timing and rates of ice sheet
121 thinning.

122 The potential to compare ice sheet model output to *rates* of change, specifically thinning rates in
123 this case, has advantages over individual measurements. Firstly, where a rate is reconstructed
124 using single nuclide SED, the derived rate will be broadly insensitive to systematic uncertainties
125 which should affect all samples within a transect proportionally. Additionally, in Antarctica scaling
126 uncertainties relating to solar modulation are minimal, however, care should be taken when
127 comparing rates that are integrated over different timescales (e.g. mid-Holocene vs. post-LGM
128 period) as these may be biased by temporal averaging of the datasets that underlie the scaling
129 model. That said, (dis)agreement between a reconstructed rate and modelled rates (n.b. *not* the
130 precise *timing* of thinning) remains a robust comparison even in the event of future refinements in
131 the dating technique. This is important where models simulate retreat at different times to
132 geological data, sometimes due to uncertainties in forcing data such as climate input. In the case
133 of point measurements, if the age changes by a given amount the data-model agreement/misfit
134 will also change by a correlated amount. Specifically, this may change the absolute agreement
135 such that model output(s) that were previously conformable with observations are now
136 incompatible. Another advantage is that a thinning rate can be reasoned on glaciological grounds
137 to be representative of ice sheet change on scales similar to, and greater than, the grid resolution
138 commonly used in modelling experiments of ice sheet evolution since the LGM (Mackintosh et al.,
139 2011; Golledge et al., 2012; DeConto and Pollard, 2016). For example, longitudinal stress-
140 coupling allows perturbations that increase mass flux through the grounding line, such as thinning
141 and/or disintegration of buttressing ice shelves, to result in rapid propagation of dynamic thinning
142 inland at distances of >100 km (Pritchard et al., 2009; Wingham et al., 2009; Reese et al., 2018).
143 Despite these advantages the use of thinning rates for model-data comparison requires that the
144 derived rate be a robust approximation of the past rate of change. This requires 1) Identification
145 and removal of data points whose apparent exposure age does not accurately reflect the true age
146 of deglaciation at a given altitude, and 2) A means of calculating a thinning rate that accounts for
147 reported uncertainties in the remaining data set.

149 **3. Methods**

150 We surveyed the online ICE-D Antarctica database (<http://antarctica.ice-d.org/>; census date:
151 November 2017) and extracted previously published data (^{10}Be and ^{26}Al) from sites where
152 exposure ages are < 25 ka and span a suitable altitudinal extent (>50 m) or were inferred by the
153 original authors to constrain thinning (Figure 2; supplemental Table S1). We consider this
154 appropriate as the AISs are likely to have been at, or very near to, their maximum extent at 25 ka
155 (Clark et al., 2009; Bentley et al., 2014). The input file(s) for all sites are included in the
156 Supplemental Data Table S2. We re-calculated the ages using the input data contained within
157 ICE-D using v3 of the CRONUS-Earth online calculators (<https://hess.ess.washington.edu/>). All
158 ages were calculated assuming zero erosion. Densities ($2.20 - 2.94 \text{ g cm}^{-3}$) are taken from the
159 original publications as per the ICE-D database. We present ages calculated using the Lal-Sato-
160 Dunai nuclide-specific (LSD_n) scaling scheme (Lifton et al., 2014). Given that subsequent
161 analyses utilise the external uncertainties and 2σ internal uncertainties our results are insensitive
162 to choice of scaling scheme or density value.

163 As a first-order quality control criterion we excluded ages with discordant (i.e. the apparent
164 exposure ages do not overlap within their respective uncertainties) $^{26}\text{Al}/^{10}\text{Be}$ ages as this
165 suggests a complex exposure history. Ages from samples currently emerging from ice or located
166 on present day blue ice moraines were not used to reconstruct thinning rates as the relationship
167 between these exposure ages and the thinning represented by ages from clasts deposited on the
168 flanks of nunataks is not clear (cf. Hein et al., 2016). These ages were however used to constrain
169 the minimum age of cessation of thinning where possible (i.e. Marble Hills and Patriot Hills). We
170 acknowledge that this approach may lead to exclusion of a small amount of potentially useful
171 data but consider it appropriate given the broad scale of our study and the future implementation
172 of the derived dataset.

173 We did not attempt to reconstruct thinning rates from sites with fewer than four exposure ages as
174 a low number of samples reduces confidence in the subsequent identification of outliers. To
175 maximise the data available we combined data-sets where exposure ages were inferred to
176 constrain thinning but quantified rates had not previously been reported. One issue that arises
177 from combining sites that extend for several km in an along-flow direction is that distal samples
178 that were exposed simultaneously can occur at different altitudes (Spector et al., 2017). Three of
179 our combined sites (Figure 2, Table 1; Sites 11 - 13) had elevations normalised with respect to
180 the modern ice surface, and an elevation projection (cf. Spector et al., 2017) was not required.
181 The other combined site (Figure 2, Table 1; Site 22) has no current glacier from which to extract a
182 gradient, hence we assumed a low gradient of 0.01 for the elevation projection. Projection
183 introduces a degree of altitudinal uncertainty, however, given the limited amount of data to which
184 this approach was applied, and the fact that the results are to be used as a first order comparison

185 to model output, we consider this acceptable. In one case (Mackintosh et al., 2007) the relatively
186 large distances between individual sites (>10 km) meant we could not confidently project altitudes
187 and thus did not include these data in further analyses. To calculate thinning rates for all other
188 sites we used normalised elevations where these were reported and raw elevations above sea
189 level where they were unreported. In total we present 25 thinning rates from 23 sites (Figure 2,
190 Tables 1 and 3). The regressed exposure ages and elevations are included in supplemental
191 Table S3.

192

193 **3.1 Bayesian Outlier detection**

194 Older and higher samples should be exposed by ice surface lowering before the lower samples.
195 This age-elevation relationship can be used to reduce the uncertainties of exposure ages (Jones
196 et al., 2015) but such an approach also allows outliers to be identified using OxCal v4.3 (Bronk
197 Ramsey, 2017; <https://c14.arch.ox.ac.uk/oxcal/OxCal.html>). The independent age measurements
198 were arranged into a relative order of exposure; the *prior model* (Buck et al., 1996; Bronk
199 Ramsey, 2008, 2009a), and assigned an initial probability (*prior probability*) of being an outlier in
200 time (*t-type* outlier cf. Bronk Ramsey, 2009b). The outlier model calculates a subsequent
201 probability (*posterior probability*) for a given measurement being an outlier. In practice the *prior*
202 *model* contains a series of independent age probability distributions (SED ages) that are often
203 overlapping. Bayesian age modelling in OxCal v4.3 uses Markov Chain Monte Carlo sampling to
204 assess the conformability of the age measurements and produce a model output of refined age
205 distributions. Where the refined age distribution of a given sample does not overlap with its un-
206 modelled initial age distribution the *posterior probability* of the sample being an outlier will
207 increase (Figure 3). We assigned each age measurement a low *prior probability* of being an
208 outlier of 0.05 (i.e. 1 in 20). OxCal produces a model agreement index (*A*) with 60 being the
209 commonly-adopted threshold value (Bronk Ramsey, 2008). If $A > 60$ then samples with an outlier
210 *posterior probability* > 0.5 (i.e. more likely to be an outlier than not (Bronk Ramsey, 2009b)) were
211 excluded from further analysis. If $A < 60$ then the model was re-run iteratively, increasing the *prior*
212 *probabilities* (i.e. down-weighting) of samples whose *posterior* > *prior*, until an acceptable *A* index
213 value was obtained (Figure 4).

214 We used the “general” outlier definition within the *Sequence* model of OxCal (Bronk Ramsey,
215 2009a), which uses a student’s t-distribution to define how outliers are distributed, and a
216 timescale of 10^0 - 10^4 years (i.e. a sample may be an outlier by a few years or by many thousands
217 of years). The *Sequence* model only requires samples to be in a stratigraphic order and it uses a
218 uniform prior (Bronk Ramsey, 2009a). This essentially assumes a linear interpolation between
219 dates akin to a linear sedimentation rate within a sedimentary sequence. The relatively large
220 uncertainties associated with exposure ages preclude identification of variable thinning rates
221 between individual samples. Where there is some constraint on the timing of maximum ice

222 surface elevation, such as samples from a high lateral moraine or above a weathering limit, we
223 imposed a *Boundary* between those samples and the samples that are inferred to constrain
224 thinning to account for any potential abrupt shift in the rate of change. In some cases, where
225 there was a significant temporal gap between vertically adjacent samples, a *Boundary* was
226 required to obtain a conformable model. Bayesian outlier detection was undertaken on ^{10}Be ages
227 only. Given that the $^{26}\text{Al}/^{10}\text{Be}$ nuclide pair cannot discriminate short (i.e. $10^3 - 10^4$ years) periods
228 of complex exposure on the timescales we are interested in we do not think it is appropriate to
229 weight our Bayesian outlier detection to the limited number of samples where paired $^{26}\text{Al}/^{10}\text{Be}$
230 analyses are available. In total only 43 ^{26}Al analyses pass our age screening criteria thus we do
231 not consider that our results would be sensitive to their inclusion. All model outputs are included
232 in supplemental data.

233

234 **3.2 Monte Carlo Linear Regression**

235 MC linear regression analysis was undertaken using a MATLAB® model (Jones et al., 2015;
236 Jones et al., *in review*) that is based on the general approach of Johnson et al. (2014). Thinning
237 rates are generated from 5000 iterations through randomly sampled points using 2σ internal
238 uncertainties. Regressions that produce a reverse slope are excluded as implausible. The model
239 outputs the 68% and 95% ranges of thinning rates, the ‘best-fit’ thinning rate, the median thinning
240 rate, and a histogram of modelled rates. Thinning rates were calculated using ^{10}Be exposure
241 ages that produced a conformable Bayesian sequence and were not flagged as outliers (see
242 Section 3.1). Where vertical transects were punctuated by *boundaries* we estimated thinning
243 rates based on the longest continuous sequence of exposure ages between individual
244 boundaries. For consistency we calculated thinning rates from ^{10}Be exposure ages only.
245 Examples of the model output are shown in Figure 5 and all model outputs are included in
246 supplemental data.

247

248 **4. Results**

249 All transects yielded Bayesian sequences with acceptable A indices after exclusion (or suitable
250 down-weighting) of samples flagged as being potential outliers (Table 2). In general the number
251 of samples excluded represents a small proportion of the total compilation and in all but one case
252 (Thomas Hills) the number of excluded samples is <50%. Bayesian outlier analysis identifies
253 outliers on the basis that their *posterior* age probabilities are not conformable within a continuous
254 sequence representing progressive thinning. It does not differentiate between samples that are
255 “too old” and samples that are “too young”. Assessing the relative likelihood of processes that act
256 to make an age “too young” or “too old” is best carried out by the field workers. As we compiled
257 previously published datasets we cannot make that appraisal. Considering this fact, and to retain

258 objectiveness and reproducibility, we did not manually re-introduce 'young' erratics flagged as
259 outliers into the MC analysis that produced the thinning rates presented in Table 3. In total 6
260 samples from 5 transects were excluded as being 'too young' (Table 6).

261 The modelled thinning rates obtained by the MC approach outlined here are summarised in
262 Figure 6 and Table 3. Thinning rates range from 0.01 – 6.41 m yr⁻¹ (1 σ ; 68%) and 0.02 – 37.72 m
263 yr⁻¹ (2 σ ; 95%) with best fit thinning rates ranging from 0.02 – 1.67 m yr⁻¹ and median rates ranging
264 from 0.02 – 1.57 m yr⁻¹. For ease of discussion we quote the 'best-fit' rate when outlining rates
265 from individual sites as this metric best illustrates contrasts in rate. At two sites, Pourquoi-Pas
266 Island and Thomas Hills, the 'best-fit' regression produced a negative slope and is not reported.
267 For these sites we instead use the median rate while acknowledging that the exposure age data
268 implies a potentially much higher rate of thinning.

269 The results from transects that have previously been used by other authors to calculate thinning
270 rates are somewhat comparable to these previously published rates (Table 4) with notable
271 exceptions of Mount Moses (Figure 2, Site 10; Johnson et al., 2014), Low Ridge (Site 5; Jones et
272 al., 2015), and the Marble Hills (Site 14; Hein et al., 2016). For Mount Moses and Low Ridge this
273 is because the samples are in age stratigraphic order and, as per our protocol, thinning rates
274 were calculated from all samples. The original studies identified a change in thinning rate, and
275 calculated their rate from the uppermost samples that defined the period of more rapid thinning.
276 For comparison we also calculated thinning based on these upper samples and obtained a
277 similar rate (Table 4). These values are included in Table 3 as alternative thinning rates from
278 Mount Moses and Low Ridge. Given the close agreement between the higher rates and those
279 from neighbouring sites - Maish Nunatak (Figure 2, Site 9), and Mount Suess/Gondola Ridge
280 (Site 3) - we use the rapid thinning rates in further discussions. For the Marble Hills (Site 14) our
281 best-fit rate is somewhat lower (0.08 m yr⁻¹) than the rate quoted by Hein et al. (2016) (0.21 m yr⁻¹).
282 This is because we combined all samples from the Marble Hills (Bentley et al., 2010; Hein et
283 al., 2016) and, on the basis of our approach to outlier detection and removal, our rate is
284 calculated from a different sub-set of these samples compared with the rate of Hein et al. (2016).
285 When we used only the same samples we obtained a similar rate of 0.28 m yr⁻¹.

286 Both Bayesian and MC analyses provide estimates of the timing of thinning onset and cessation
287 (Table 5). As the thinning rates discussed in this paper are derived from the MC analysis the
288 discussion regarding timings of thinning focuses on the MC derived estimates. It is important to
289 note that the estimates of thinning onset/cessation are maximum and minimum constraints
290 respectively. As identified by previous studies (e.g. Bentley et al., 2017; Johnson et al., 2014;
291 Jones et al., 2015; Hein et al., 2016) widespread thinning occurs during the Holocene at
292 numerous locations throughout East and West Antarctica. The earliest onset of thinning at c. 12
293 ka occurs in the Ross Sea region of the Transantarctic Mountains (Mount Hope (Figure 2, Site 1)
294 and Mount Rigby/Karo (Site 2); Spector et al., 2017). At the other sites thinning onset is focussed

295 in the early to mid-Holocene. The latest inferred onset of thinning occurs at c. 3 ka at Mount Rea
296 (Figure 2, Site 16); Stone et al., 2003), although early Holocene thinning onset is also recorded at
297 nearby sites; Mount Darling (Site 17) and Mount Valkenburg (Site 18; Stone et al., 2003). The
298 transect locations, reconstructed rates and modelled onset/cessations are combined and
299 included as supplementary Table S4.

300

301 **5. Discussion**

302 **5.1 Considerations when using MC analysis to model thinning rates**

303 Bayesian outlier analysis identifies outliers on the basis that their *posterior* age probabilities are
304 not conformable within a continuous sequence representing progressive thinning. It does not
305 differentiate between samples that are “too old” and samples that are “too young”. In total 6
306 samples from 5 transects were excluded as being ‘too young’. (Table 6). The specific effect of
307 manually inserting these ‘outliers’ depends on their location within the vertical transect and the
308 number of other samples considered in the regression analysis. A linear regression line intersects
309 with the mean of the predictor and response variables. Consequently, if a predictor value (i.e.
310 elevation) is far from the mean then an extreme response value (i.e. young age due to transient
311 shielding) will lead to a larger change in the regression slope (Figure 7; cf. Altman and
312 Kryzywinski, 2016). The best fit thinning rate, defined by the regression slope, is thus most
313 sensitive to extreme ages at the top and bottom of the vertical transect. In contrast, samples with
314 extreme ages located near the mean of the elevation distribution have lower influence on the
315 regression slope.

316 This sensitivity to a sample’s elevation has some important implications. If a sample is
317 conformable but is not an accurate exposure age due to undetected geological uncertainty it will
318 influence the estimated thinning rates. For example, a small amount of inheritance within samples
319 at the upper and lower limits of an elevation transect can act to reduce and increase the best-fit
320 thinning rates respectively. In general transects with smaller numbers of samples, particularly
321 where these are unevenly distributed in space and/or define monotonic thinning, are likely to be
322 most sensitive to the effects of undetected geological uncertainty. This is well illustrated at
323 Thomas Hills (Figure 2, Site 12) where the samples are clustered towards the upper and lower
324 ends of the transect and the modelled thinning rates – 1.57 m yr⁻¹ (median); 0.36–37.72 m yr⁻¹
325 (95% range) – are the highest and most widely distributed in our compilation. It is notable that
326 these rates are significantly higher than those from nearby sites (Williams Hills (Figure2, Site 11),
327 Mount Harper/Bragg (Site 13)). This may reflect site specific conditions, such as a particularly
328 extreme windscoop or local flow re-organisation, or alternatively the Thomas Hills data set may
329 be influenced by geological uncertainty. Specifically, if inheritance was prevalent in the lower-
330 most samples, but to an extent that did not make samples unconformable, then this geological
331 uncertainty would be undetected by our analysis. Ideally, multiple samples from similar elevations

332 would allow outliers to be identified using statistical approaches (e.g. Balco, 2011; Jones et al., *in*
333 *review*; Rinterknecht et al., 2006). However, there are numerous reasons why this may not be
334 possible including adequate resources, lithology, sample availability, and restricted time on the
335 ground.

336 Linear regression implicitly averages the rate of change over the period of observation and as
337 such precludes identification of variations in the rate of thinning. For many sequences the scatter
338 of exposure ages and their inherent uncertainties (even after identification and removal of
339 outliers) may make identification of such variations in thinning rate exceedingly difficult. However
340 for more coherent sequences of exposure ages, particularly those that span longer timeframes
341 (e.g. Spector et al., 2017), there may be useful information regarding the timing of changes in
342 thinning rate if they can be identified. Johnson et al. (2014) used a two-segment, piecewise
343 regression for the Mount Moses data-set to define a change in the thinning rate implied by a
344 distinct break in slope in a simple linear interpolation between the exposure ages. This approach
345 relies on such a break of slope being identifiable, which may not always be the case. A potential
346 alternative approach to account for temporal changes in thinning rate is to use a time-dependent
347 statistical model in a similar way to approaches employed in reconstructing rates of sea-level
348 change (e.g. Cahill et al., 2015; Kemp et al., 2017; Khan et al., 2015). Examining residual plots
349 from a simple linear regression is one potential means to identify transects where time variable
350 rates may be appropriate. Subsequently, a spline-based model could allow continuous and
351 dynamic evolution of thinning rate changes to be estimated (Jones et al., *in review*).

352

353 **5.2 Discussion of reconstructed palaeo-thinning rates**

354 **5.2.1 Comparison to modern thinning rates**

355 Modern rates of ice surface changes in Antarctica are primarily quantified through satellite
356 observations, specifically satellite altimetry (c.f. Shepherd et al., 2018) and whilst some areas are
357 thinning, the rates are highly variable, with some parts of Antarctica showing little change or even
358 thickening (Pritchard et al., 2009; McMillan et al., 2014). Additionally, the spatial scale over which
359 rates are quantified is also variable with some rates being presented as basin averages while
360 others are more limited in space (e.g. thinning rates close to a grounding line). We compiled a
361 number of published thinning rates for comparison to the reconstructed palaeo-rates. This is not
362 an exhaustive compilation of modern rates but is intended to show the range of reported rates
363 from satellite observations.

364 Overall, the modelled palaeo-thinning rates are generally lower than modern thinning rates
365 measured by satellite altimetry although notably there is some overlap in the ranges (Figure 8
366 and Table S1). Specifically, the overlap occurs in those palaeo-observations that correspond to
367 centennial observation intervals which have a similar range to modern (annual to decadal) rates.

368 Palaeo-rates that are derived from exposure ages that span longer ($>10^3$ years) observation
369 intervals are lower. There are a couple of potential explanations for this pattern. Modern
370 observations demonstrate that thinning is focused in the central portions of ice streams (e.g.
371 Shepherd et al., 2001; Wingham et al., 2009). In the case of Pine Island Glacier, the rates of
372 thinning within the main trunk of the ice stream and the average for the entire drainage basin
373 differ by an order of magnitude ($>2\text{ m yr}^{-1}$ vs 0.11 m yr^{-1} ; Wingham et al., 2009). This difference is
374 driven by lower rates of thinning in areas of slow flow (Wingham et al., 2009). These areas
375 correspond to areas of ice overlying topographic/bedrock highs between faster flowing ice
376 corridors. The fast flowing areas generally correspond to deeper subglacial troughs where ice
377 flow is accelerated by basal sliding and lateral drag is minimal (Stenoien and Bentley, 2000;
378 Shepherd et al., 2001). The SED data used to reconstruct palaeo-thinning rates are, by
379 necessity, collected from topographic bedrock highs as these form the exposed rock areas
380 required for applying the technique, potentially explaining the general lower thinning rates
381 reconstructed in the past.

382 Another potential explanation relates to the disparity in temporal sampling resolution between
383 modern observations and palaeo-data. Modern observations span the last couple of decades with
384 thinning rates often calculated from a few years of data so, on geological timescales, these
385 represent point measurements. Conversely, palaeo-rates are reconstructed from data that span
386 100's to 1000's of years and these rates represent a time-averaging of thinning rates that likely
387 varied to be both faster and slower than the long-term average. It is implicit that high rates of
388 dynamic thinning cannot be maintained at any location over long (10^3) timescales and are
389 relatively short-lived events, an inference reflected by the fact that the highest paleo-rates
390 correspond to sites where the data span a relatively shorter period of time (Figure 8). As dynamic
391 thinning progresses the spatial pattern changes (cf. Shepherd et al., 2001; Wingham et al., 2009).
392 A given location will experience different flow regimes as the drainage basin evolves through time
393 due to retreat/stabilisation of the grounding line, ice divide migration etc. This may be a potential
394 explanation for any sites where variable rates of thinning can potentially be identified and
395 quantified. A thinning rate reconstructed from a given location not only represents an average
396 through time but also a quasi-spatial average. That is, over long timescales a thinning rate will be
397 more reflective of the basin average than of the higher measurements of thinning within the main
398 glacier trunk. The lower rates reconstructed in the past may therefore, at least partially, reflect an
399 averaging effect.

400 The overlap of modern and palaeo-rates suggests that modern rates of thinning may be
401 consistent with those that occurred during the Holocene in various parts of Antarctica.
402 Importantly, the overlap at centennial timescales implies that dynamic thinning, once initiated, can
403 be sustained for hundreds of years. This implication was previously highlighted by Johnson *et al.*,
404 (2014) for the Pine Island Glacier catchment (Figure 2, Sites 9 and 10) but it may be speculated

405 that the potential for centennial scale thinning and associated grounding line retreat may be
406 pervasive across Antarctica.

407

408 *5.2.2 Spatial and temporal patterns of thinning rates and potential implications*

409 Sites with the highest inferred palaeo-thinning rates are located in the Amundsen Sea sector of
410 West Antarctica (Maish Nunatak and Mount Moses) and the Antarctic Peninsula (Pourquoi-Pas
411 Island; Figure 9). These are both locations where modern observations record rapid changes in
412 ice surface geometries. In the Amundsen Sea sector satellite observations record contemporary
413 thinning rates of 1 - >4 m yr⁻¹ within the trunk of Pine Island Glacier (e.g. Wingham et al., 2009;
414 Park et al., 2013) with comparable rates from nearby Thwaites Glacier (Shepherd et al., 2002;
415 Pritchard et al., 2009). In the Antarctic Peninsula thinning of outlet glaciers has been observed in
416 connection with the thinning and breakup of buttressing ice shelves with rates ranging from c.1.5
417 - 3 m yr⁻¹ (Wouters et al., 2015; Friedl et al., 2018) to >10 m yr⁻¹ (Rignot et al., 2004; Scambos et
418 al., 2004).

419 In the Amundsen Sea the primary driver of ice shelf thinning is inferred to be oceanic with
420 increased influx of warm Circumpolar Deep Water (CDW) at depths exceeding 300 m driving
421 increased melting in the sub-ice shelf cavity (Rignot and Jacobs, 2002; Jenkins et al., 2010;
422 Jacobs et al., 2011). This process has been cited as the driver of contemporary thinning across a
423 wide swathe of the West Antarctic margin (Pritchard et al., 2012). In the Antarctic Peninsula rising
424 air temperatures have been correlated with the breakup of fringing ice shelves (Vaughan and
425 Doake, 1996) but other studies have invoked oceanic forcing as the primary driver of melting (e.g.
426 Wouters et al., 2015). Although a contribution from atmospheric forcing is likely, the widespread
427 extent of contemporary thinning, even in areas where atmospheric forcing is insignificant, points
428 to the ocean as a primary driver of the observed changes. Under this assumption the correlation
429 in the locations of the high modelled palaeo-thinning rates and the highest observed modern
430 rates is notable and suggests that a common oceanic forcing could have been prevalent during
431 deglaciation (cf. Smith et al., 2007; Hillenbrand et al., 2017) although the influence of trough
432 geometry is also likely to play a key role in determining the absolute magnitude of thinning
433 (Jamieson et al., 2014; Jones et al., 2015). That said, for rapid thinning to occur requires an initial
434 driver before the positive feedback influences of reverse bed slopes and/or deep troughs are fully
435 engaged. Notably, Pourquoi-Pas Island (Figure 2, Site 11), where thinning may have been rapid
436 – as implied by the negative slope of the best-fit regression – is located on the western margin of
437 the Antarctic Peninsula which is thought to be particularly sensitive to changes in the Antarctic
438 Circumpolar Current and associated influxes of CDW (Bentley et al., 2009). Additionally, there is
439 evidence of southward penetration of warm CDW waters during the early-mid Holocene from
440 sediment cores in Palmer Deep (Leventer et al., 2002) and Pine Island Bay (Hillenbrand et al.,
441 2017). This presence of warm water coincides broadly with the modelled timing of thinning

442 around Pine Island Glacier at 8.5–7.5 ka (cf. Johnson et al., 2014). Given the indications that
443 CDW was present in the Amundsen and Bellingshausen Seas during the earliest Holocene
444 (Hillenbrand et al., 2017; Peck et al., 2015) it can be speculated that the rapid thinning at
445 Pourquoi-Pas Island was potentially related to grounding line retreat and/or a decrease in
446 buttressing from fringing ice shelves at c.11.6 ka. This timing is broadly co-incident with marine
447 foraminiferal records and radiocarbon ages that constrain initial outer shelf deglaciation of the
448 Marguerite Bay Ice Stream at c.13 ka, with retreat of grounded ice from the inner portion of
449 Marguerite Bay more proximal to Pourquoi-Pas Island by c.9.5 ka (Heroy and Anderson, 2007;
450 Kilfeather et al., 2011).

451 The two sites on the eastern Antarctic Peninsula have lower modelled thinning rates than PQP on
452 the western Antarctic Peninsula. While we cannot completely exclude the possibility that these
453 differences reflect effects of sampling resolution the sites span a comparable altitudinal range
454 and do not exhibit any evidence for a significant step change in thinning rate. Consequently, while
455 acknowledging that the data points are limited, we suggest that the difference in modelled
456 thinning rates represents a real difference between the eastern and western Antarctic Peninsula.
457 This may reflect a reduced influence of CDW on the eastern side of the Antarctic Peninsula (cf.
458 Hodgson et al., 2006; Bentley et al., 2009) leading the ice shelves in this area to be more resilient
459 and preserving their buttressing effect. Additionally, there is a difference in the timing of thinning
460 onset between the western and eastern Antarctic Peninsula sites. This is consistent with previous
461 suggestions of earlier deglaciation on the west side compared with the east (Evans et al., 2005;
462 Ó Cofaigh et al., 2005; Hodgson et al., 2006; Bentley et al., 2009). However, given the limited
463 amount of data, these observations remain speculative and further studies on early Holocene
464 glacier evolution in the Antarctic Peninsula are required to further elucidate the controls on
465 deglaciation.

466 Broadly, palaeo-thinning rates in the interior parts of the Weddell and Ross Sea sectors are lower
467 than the rates observed at sites more proximal to the ocean (with the notable exception of the
468 Thomas Hills – discussed in section 5.1). This is evident in the Ross Sea sector where rates
469 decrease as latitude increases. Modern observations demonstrate that dynamic thinning occurs
470 at higher rates closer to the grounding line. For example on Pine Island Glacier thinning rates, as
471 measured by in situ GPS, decrease from 3.65 m yr⁻¹ at a distance of 55 km from the grounding
472 line to 1.05 m yr⁻¹ at 171 km from the grounding line (Scott et al., 2009). The interior
473 Weddell/Ross Sea sites where palaeo-thinning is recorded would have been located further from
474 the grounding line as it retreated following the LGM (cf. Bentley et al., 2014) and were likely less
475 susceptible to rapid thinning. Additionally, these inner sites have likely retained the buttressing of
476 the Ronne-Filchner and Ross Ice Shelves throughout much, if not all, of the Holocene.

477 At all sites thinning is focused in the Holocene (cf. Hein et al., 2016; Spector et al., 2017). In the
478 Ross Sea sector there is a complex temporal and spatial pattern of thinning onset. The earliest

479 modelled onset occurs at sites 1 and 2, (Beardmore and Shackleton Glaciers; cf. Spector et al.,
480 2017) where thinning begins at c. 12 ka. Further to the south, sites 6-8 evidence thinning onset
481 after 10 ka. Earlier thinning onset at more northerly sites could be inferred to reflect a general
482 North–South migration of the grounding line (cf. Conway et al., 1999; Ackert, 2008) with
483 concomitant reduction in buttressing stresses first affecting more northerly sites. However, this
484 simple scenario does not account for the later onset of thinning at c. 7 ka at Mackay Glacier (cf.
485 Jones et al., 2015). Recent studies have proposed a more complex model of Ross Sea Basin
486 deglaciation that accounts for bathymetry and incorporates early deglaciation of the central Ross
487 Sea Basin and an early Holocene readvance of East Antarctic outlet glaciers (Halberstadt et al.,
488 2016; Lee et al., 2017). It may be that the later thinning of Mackay Glacier relates to retreat from
489 this readvance rather than early Holocene deglaciation of the central Ross Sea. The complexity
490 in the temporal pattern of thinning is also observed at sites 16-19 (Figure 10; Stone et al., 2003),
491 where thinning begins at different times between 9 ka and 3 ka within a relatively restricted
492 geographical area. Within the Weddell Sea sector the onset of thinning ranges from 9.4 – 7.4 ka
493 in the Ellsworth Mountains (Figure 10, sites 14 and 15; Bentley et al., 2010; Hein et al., 2016) and
494 8.7 – 5.8 ka in the Pensacola Mountains (Figure 10, sites 11-13; Balco et al., 2016; Bentley et al.,
495 2017). Importantly, the geological data do not directly evidence a single common forcing for
496 thinning as they record thinning occurring in different places at different times. Instead the data
497 highlight a complex response of the AISs to external forcing factors. This response was likely
498 influenced by internal feedbacks, such as trough geometry, resulting in temporal variability in
499 thinning onset during deglaciation.

500 Despite this complexity the overall timing of thinning does allow some inferences to be drawn
501 regarding Antarctica's contribution to sea-level rise during the last deglaciation. Firstly, as noted
502 above, all sites evidence thinning commencing from the early Holocene onwards (Figure 11).
503 Antarctica has been proposed as a major contributor to Meltwater Pulse 1A (MWP-1A) (Clark et
504 al., 2002; Weber et al., 2014), a eustatic sea-level rise of >10 m dated to 14.7-14.3 ka
505 (Deshcamps et al., 2012). No thinning rate sites have MC estimates of thinning onset that overlap
506 with the timing of MWP-1A (Figure 11), with thinning focused in the Holocene at all sites (cf. Hein
507 et al., 2016; Spector et al., 2017). While acknowledging that the MC estimates of thinning onset
508 are minimum ages it may be expected that, if thinning was ongoing at these sites during MWP-
509 1A, then at least some of the thinning onset ages would overlap or pre-date this time. Notably, at
510 sites with constraints on maximum ice elevation (e.g. weathering limit or moraine) such as those
511 in the Ellsworth Mountains (Bentley et al., 2010; Hein et al., 2016), Prince Charles Mountains
512 (White et al., 2011), and the Transantarctic Mountains (Todd et al., 2010; Jones et al., 2015),
513 thinning onsets, as constrained by the Bayesian boundary ages, also significantly post-date
514 MWP-1A. It is important to emphasise that the current absence of evidence is not evidence of
515 absence and an Antarctic contribution to MWP-1A could be sourced from areas of Antarctica
516 without suitable SED data (e.g. most of East Antarctica, or the central Ross Sea/Weddell Sea

517 embayments). However the evidence presented here accords with recent studies that have not
518 identified the potential Antarctic sources of MWP-1A from terrestrial studies using SED (Bentley
519 et al., 2014; Spector et al., 2017).

520 Finally, some data-constrained models have Antarctica's contribution to deglacial sea-level rise
521 continuing into the Holocene (Mackintosh et al., 2011; Argus et al., 2014; Briggs et al., 2014). Our
522 compilation, while including some of the said data constraints, also includes newly available data
523 not used in those models. All available SED sites with constraints on Antarctic thinning since the
524 LGM currently suggest that the majority of mass loss from these sectors occurred during the
525 Holocene, with widespread thinning occurring in the mid-Holocene (Figure 11). This timing of
526 mass loss is also consistent with estimates of the timing of Antarctic deglaciation derived from
527 far-field eustatic sea-level records (Mauz et al., 2015).

528

529

530 **6. Conclusions**

531 We have compiled exposure ages from a total of 23 sites around Antarctica that constrain, or
532 have the potential to constrain, past ice sheet thinning. By taking a consistent approach to quality
533 control and modelling of past thinning rates we present an internally consistent data set for use in
534 a forthcoming model-data comparison exercise. This is the first compilation of palaeo-thinning
535 rates in Antarctica and provides an opportunity to compare the modelled rates to contemporary
536 patterns and magnitudes of thinning.

537 Thinning rates, as determined by MC linear regression analysis, are sensitive to the distribution of
538 exposure ages, both in time and space. Consequently, sampling strategies can be designed to
539 account for this with accurate constraints from the top and bottom of a transect being the most
540 important for use in linear regression analysis. MC analysis can produce both ranges and single
541 values (best fit, median) for past thinning rates. These values can be sensitive to, and are
542 influenced by, the distribution of exposure ages within transects. Consequently, there remains a
543 need to use some degree of subjective judgement, both in deciding which metric to use in model-
544 data comparisons, and in interrogating the data in the cases of disagreement.

545 When constrained over centennial timescales past rates of thinning are comparable to modern
546 rates. This implies that modern thinning has the potential to be sustained for some time into the
547 future. Palaeo-thinning rates are lower than modern observations when constrained on millennial
548 timescales. This difference is potentially due to the locations of sampling sites within ice drainage
549 basins and/or averaging effects when the periods of time over which past thinning rates are
550 reconstructed are orders of magnitude greater than the length of modern observations. Notably
551 the highest palaeo-rates of thinning occur in regions that are characterised by high rates of
552 contemporary thinning, namely the Amundsen Sea and Antarctic Peninsula regions, suggesting

553 that similar mechanisms to those that drive modern thinning may have operated in the past. Both
554 the MC analysis and Bayesian outlier detection produce age estimates for the onset of past
555 thinning. Although these constraints are usually minimum ages for thinning onset they all post-
556 date MWP-1A, and no transect has thinning occurring during MWP-1A (as constrained by the
557 exposure ages). This suggests that any Antarctic contribution to this event may have been
558 sourced from regions of the continent away from SED sites constraining thinning.

559

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900

901 **Figure Captions**

902 Figure 1. Schematic diagram illustrating how samples from vertical transects can constrain past
903 ice sheet surface elevation and thinning. The left hand panels illustrate exposure ages from a
904 vertical transect and the evolution of the ice sheet surface from the LGM (t_0) to present. The right
905 hand panels illustrate the concomitant evolution of a sample's ^{10}Be inventory under the scenarios.
906 (A) The LGM ice sheet surface overtopped the uppermost sample which provides only a
907 minimum constrain on ice sheet surface elevation. (B) The LGM ice sheet surface is below the
908 uppermost surface and a sample (Sample B) from a lateral moraine constrains the timing and
909 surface elevation of the LGM. In both scenarios thinning is constrained by samples with
910 progressively lower concentrations of ^{10}Be , which would yield progressively younger exposure
911 ages. In scenario B the uppermost sample becomes saturated with ^{10}Be .

912

913 Figure 2. Location map of Antarctica showing place names mentioned in the text and locations of
914 transects where exposure ages are used to constrain past thinning rates. These are numbered as
915 per Table 1. PIG = Pine Island Glacier, ThG = Thwaites Glacier, LG = Lambert Glacier, AmIS =
916 Amery Ice Shelf, FIS = Filchner Ice Shelf, PIB = Pine Island bay, MB = Marguerite Bay. Base
917 map is from Quantarctica GIS package compiled by the Norwegian Polar Institute
918 (<http://www.quantarctica.org/>).

919

920 Figure 3. Bayesian age model output from OxCal 4.3 (Bronk Ramsey, 2017) for a simple
921 sequence of exposure ages from a vertical transect (Sample 1 being the uppermost sample). The
922 measured age distributions are shown in light grey with refined age distributions in darker grey. In
923 this example Sample 4 was flagged as an outlier. The Bayesian model produces a refined age
924 estimate for all samples, however for our purposes these were not considered in the Monte Carlo
925 analysis. The black bars represent 68% and 95% confidence intervals. The modelled age
926 distributions for the *boundaries* ("top" and "bottom") provide minimum and maximum constraints
927 on thinning onset and cessation respectively.

928

929 Figure 4. Flow chart of the approach taken to detect outliers using OxCal 4.3. See text for further
930 description.

931

932 Figure 5. Example output from the Monte Carlo linear regression analysis. Transects from; A)
933 Mount Hope (Spector et al., 2017), and B) Maish Nunatak (Johnson et al., 2014) with resulting
934 distribution of modelled thinning rates (C: Mount Hope, D: Maish Nunatak) at 68% (dashed
935 vertical lines) and 95% (dotted vertical lines). Note the x-axis is logarithmic. Note that the Maish

936 transect has a skewed distribution with a wider range of modelled thinning rates and a distinctly
937 different median rate (red vertical line) vs. the 'best-fit' rate (blue vertical line).

938

939 Figure 6. Box and whisker plot summarising the modelled palaeo-thinning rates presented here.
940 The box represents the 68% range, the whiskers represent the 95% range. The median thinning
941 rate from the Monte Carlo analysis is shown with the target symbol, the 'best fit' thinning rate
942 based on a linear regression through the mean values of the exposure ages is shown with the red
943 diamond. Transect ID numbers are as per Table 3. Note that the y-axis is logarithmic.

944

945 Figure 7. The effect of extreme values on the gradient of a linear regression. (A) A hypothetical
946 data-set of exposure ages showing a clear age-elevation trend. (B) The same data-set but with a
947 younger exposure age from the middle elevation of the transect. (C) The same data-set as A but
948 with a younger age from the bottom elevation of the transect. Note that the difference in 'best fit'
949 thinning rates is greater for the second scenario.

950

951 Figure 8. Scatter plot of modern thinning rates (blue triangles) and palaeo thinning rates (red
952 triangles) against the length of observations in years. For the palaeo-rates the duration of thinning
953 is taken from the midpoints of the 95% modelled age distributions from the Monte Carlo linear
954 regression analysis. Note that the axes are logarithmic. Triangles labelled *a* and *b* are the
955 thinning rates from Mount Moses and Low Ridge respectively as calculated using all exposure
956 ages from each site (cf. Johnson et al., 2014; Jones et al., 2015).

957

958 Figure 9. Palaeo-rates of thinning (circles) are shown against modern thinning rates (Pritchard et
959 al., 2009) and present day ocean temperatures at 500 m depth (Locarnini et al., 2013; data from
960 Quantarctica GIS package). Base map is from Quantarctica GIS package compiled by the
961 Norwegian Polar Institute (<http://www.quantarctica.org/>).

962

963 Figure 10. Spatial distribution of the onset of thinning as inferred from the midpoint of the 95%
964 modelled onset from the Monte Carlo linear regression analysis. Base map is from Quantarctica
965 GIS package.

966

967 Figure 11. Monte Carlo modelled age ranges (95%) for onset of thinning plotted alongside ice
968 volume equivalent global sea-level changes (dark blue line: Lambeck et al., 2014) and a
969 modelled Antarctic contribution to sea-level change (dark red line: Briggs et al., 2014). The timing

970 of meltwater pulse 1A (MWP-1A) is shown with the blue shading (Deschamps et al., 2012).
971 Transects are numbered as per Table 1.

972 Table 1. Location information of sites from which thinning rates are presented. ID numbers are
 973 used in subsequent figures. Elevation range is difference in altitude of uppermost and lowermost
 974 samples.

Site	Reference(s)	ID No.	Latitude (DD)	Longitude (DD)	Elevation range (m)
Mount Hope	Spector et al., 2017	1	-83.51	171.40	719
Mount Rigby/Karo	Spector et al., 2017	2	-85.52	-154.52	727
Mount Suess/Gondola	Jones et al., 2015	3	-77.04	161.64	208
Gondola (mid-lower)	Jones et al., 2015	4	-77.00	161.76	61
Low Ridge	Jones et al., 2015	5	-76.99	162.28	202
Reedy Glacier (Quartz Hills)	Todd et al., 2010	6	-85.90	-132.57	160
Reedy Glacier (Pip's Peak)	Todd et al., 2010	7	-85.43	-135.90	151
Reedy Glacier (Cohen's Nunatak)	Todd et al., 2010	8	-85.40	-136.20	104
Maish Nunatak	Johnson et al., 2014	9	-74.59	-99.45	99
Mount Moses	Johnson et al., 2014	10	-74.55	-99.20	141
Williams Hills	Balco et al., 2016; Bentley et al., 2017	11	-83.68	-58.81	413
Thomas Hills	Balco et al., 2016; Bentley et al., 2017	12	-84.38	-65.52	291
Mount Harper/Bragg	Bentley et al., 2017	13	-84.07	-57.06	236
Marble Hills	Bentley et al., 2010; Hein et al., 2016	14	-80.26	-82.13	485
Patriot Hills	Bentley et al., 2010; Hein et al., 2016	15	-80.33	-81.49	247
Mount Rea	Stone et al., 2003	16	-77.07	-145.57	572
Mount Darling	Stone et al., 2003	17	-77.27	-143.33	227
Mount Valkenburg	Stone et al., 2003	18	-77.31	-142.11	75
Fosdick Mountains	Stone et al., 2003	19	-76.54	-144.50	225
Mount Stinear	White et al., 2011	20	-73.04	66.42	323
Porquoi-Pas Island	Bentley et al., 2011	21	-67.59	-67.26	266
James Ross Island	Johnson et al., 2011; Glasser et al., 2014	22	-63.80	-57.83	198
Sjorden-Boydell	Balco et al., 2013	23	-64.23	-59.02	319

975

976

977 Table 2. Summary of total number of samples, final *OxCal* Bayesian agreement index (A) and
 978 total number of outliers excluded from each site.

979	Site	No. of samples	Final Bayesian A_{overall}	Outliers excluded
980	Mount Hope	28	62.5	4
981	Mount Rigby/Karo	21	124.1	0
982	Mount Suess/Gondola Upper	16	103.9	0
983	Gondola (mid-lower)	12	78	0
984	Low Ridge	10	123	1
985	Reedy Glacier (Quartz Hills)	25	64.6	10
986	Reedy Glacier (Pip's Peak)	7	108.7	0
987	Reedy Glacier (Cohen's Nunatak)	5	104.8	0
988	Maish Nunatak	6	158.4	1
989	Mount Moses	6	62.9	0
990	Williams Hills	17	70.3	5
991	Thomas Hills	15	79.9	9
992	Mount Harper/Bragg	12	81	5
993	Marble Hills	28	81.1	12
994	Patriot Hills	11	119.5	3
995	Mount Rea	15	93.2	2
996	Mount Darling	5	103.3	0
997	Mount Valkenburg	4	103.8	0
	Fosdick Mountains	5	107.7	0
	Mount Stinear	12	90.3	2
	Porquoi-Pas Island	6	132.8	1
	James Ross Island	7	74.2	2
	Sjorden-Boydell	9	121	0

998 Table 3. Summary of thinning rates presented from each site derived from Monte Carlo linear regression analysis. 'Best-fit' rates are not
999 presented for two sites (Thomas Hills and Pourquoi-Pas Island) as at these sites the best fit linear regression gave a negative slope and is thus
1000 rejected as physically implausible.

Site	ID No.	Min thinning rate (68%) m yr ⁻¹	Max thinning rate (68%) m yr ⁻¹	Min Thinning rate (95%) m yr ⁻¹	Max Thinning rate (95%) m yr ⁻¹	Best fit thinning rate m yr ⁻¹	Median rate
Mount Hope	1	0.14	0.20	0.13	0.24	0.17	0.17
Mount Rigby/Karo	2	0.06	0.07	0.06	0.08	0.06	0.06
Mount Suess/Gondola Upper	3	0.12	0.32	0.09	1.20	0.17	0.17
Gondola Mid-lower	4	0.07	0.49	0.04	3.16	0.57	0.15
Low Ridge (all)	5	0.03	0.03	0.02	0.04	0.03	0.03
Low Ridge (subset n=5)	5a	0.12	0.65	0.08	3.62	0.39	0.23
Reedy Glacier (Quartz Hills)	6	0.01	0.03	0.01	0.06	0.02	0.02
Reedy Glacier (Pip's Peak)	7	0.23	0.99	0.17	5.39	0.43	0.38
Reedy Glacier (Cohen's Nunatak)	8	0.01	0.02	0.01	0.03	0.02	0.02
Maish Nunatak	9	0.19	1.24	0.12	7.09	1.16	0.38
Mount Moses (all)	10	0.06	0.12	0.05	0.21	0.08	0.08
Mount Moses (subset n= 3)	10a	0.24	1.52	0.15	10.19	1.67	0.49
Williams Hills	11	0.09	0.12	0.08	0.14	0.10	0.10
Thomas Hills	12	0.62	6.41	0.36	37.72	N/A	1.57
Mount Harper/Bragg	13	0.06	0.12	0.04	0.25	0.08	0.08
Marble Hills	14	0.06	0.09	0.06	0.12	0.08	0.08
Patriot Hills	15	0.05	0.08	0.04	0.11	0.06	0.06
Mount Rea	16	0.27	0.50	0.22	0.84	0.35	0.35
Mount Darling	17	0.04	0.05	0.04	0.05	0.04	0.04
Mount Valkenburg	18	0.02	0.03	0.02	0.03	0.02	0.02
Fosdick Mountains	19	0.08	0.09	0.08	0.09	0.09	0.09
Mount Stinear	20	0.20	1.19	0.13	6.86	0.76	0.38
Porquoi-Pas Island	21	0.25	1.81	0.16	12.35	N/A	0.53
James Ross Island	22	0.05	0.16	0.04	0.73	0.08	0.09
Sjorden-Boydell	23	0.08	0.09	0.07	0.10	0.08	0.08

1002 Table 4. Comparison of thinning rates presented here and rates presented in original studies.

Reference	Site	Metric	Published rates (m yr-1)	This study (m yr-1)	Notes
Hein et al., 2016	Marble Hills	mean ± 1 s.d	0.21 ± 0.03	0.08 (median)	0.28 m yr-1 with samples used by Hein
Hein et al., 2016	Patriot Hills	mean ± 1 s.d	0.07 ± 0.01	0.06 (median)	-
Johnson et al., 2014	Mount Moses	95% range	0.08 - 5.90	0.05 - 0.21	0.15 - 10.45 m yr-1 (95%) when using three upper samples (cf. Johnson et al., 2014)
Johnson et al., 2014	Mount Moses	best fit	1.67	0.08	1.67 m yr-1 (best fit) when using three upper samples
Johnson et al., 2014	Maish Nunatak	95% range	0.13 - 5.50	0.12 - 7.09	-
Johnson et al., 2014	Maish Nunatak	best fit	1.12	1.16	-
Jones et al., 2015	Mount Suess/Gondola upper	95% range	0.33 - 0.80	0.09 - 1.07	-
Jones et al., 2015	Low Ridge	95% range	0.08 - 3.59	0.02 - 0.04	0.08 - 3.62 (95%) when using upper 5 samples (cf. Jones et al., 2015)

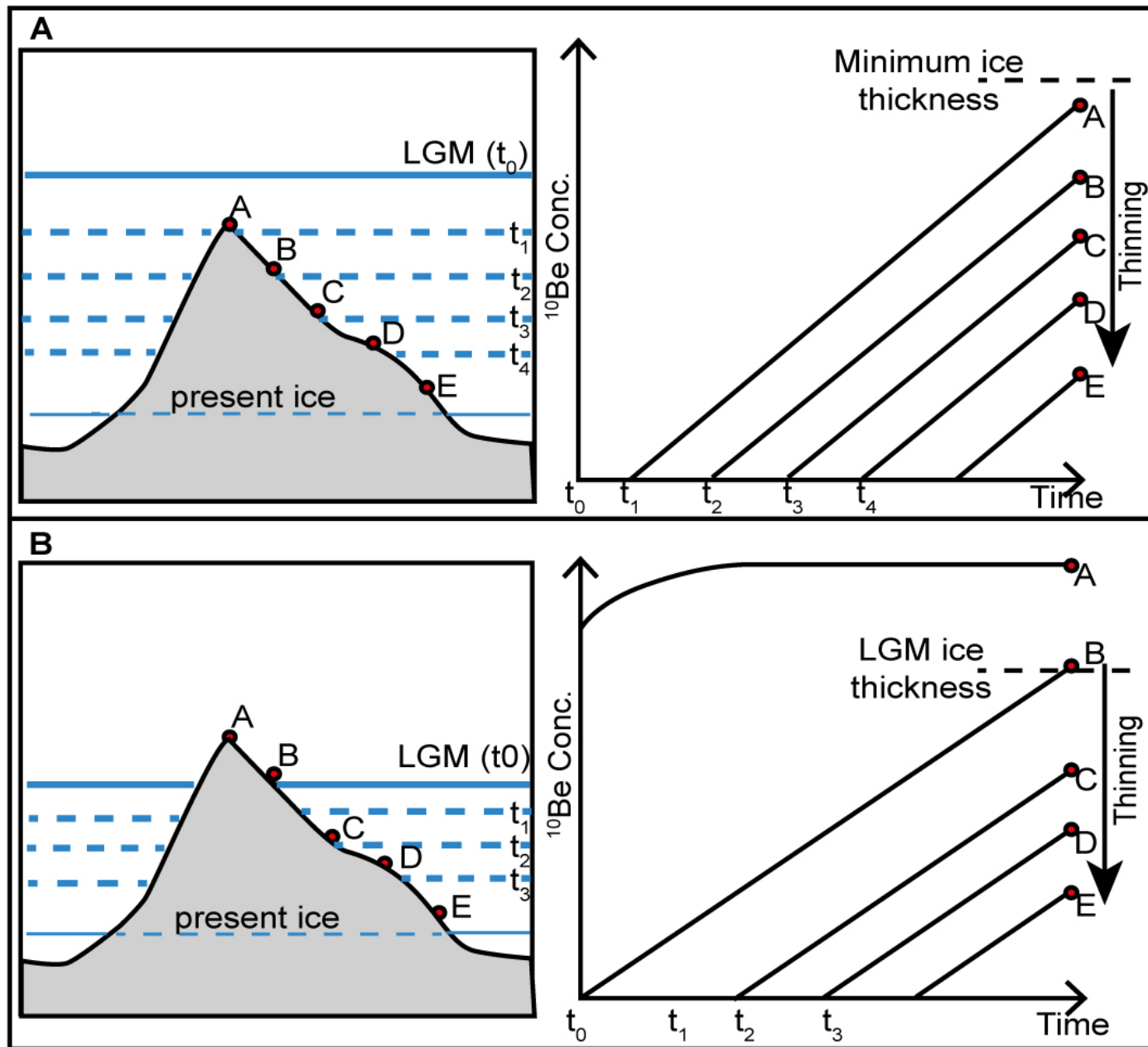
1004 Table 5. Modelled timings for the onset and end of thinning as derived from Monte Carlo (MC) linear regression analysis and OxCal 'Boundary'
 1005 command within Sequence model.

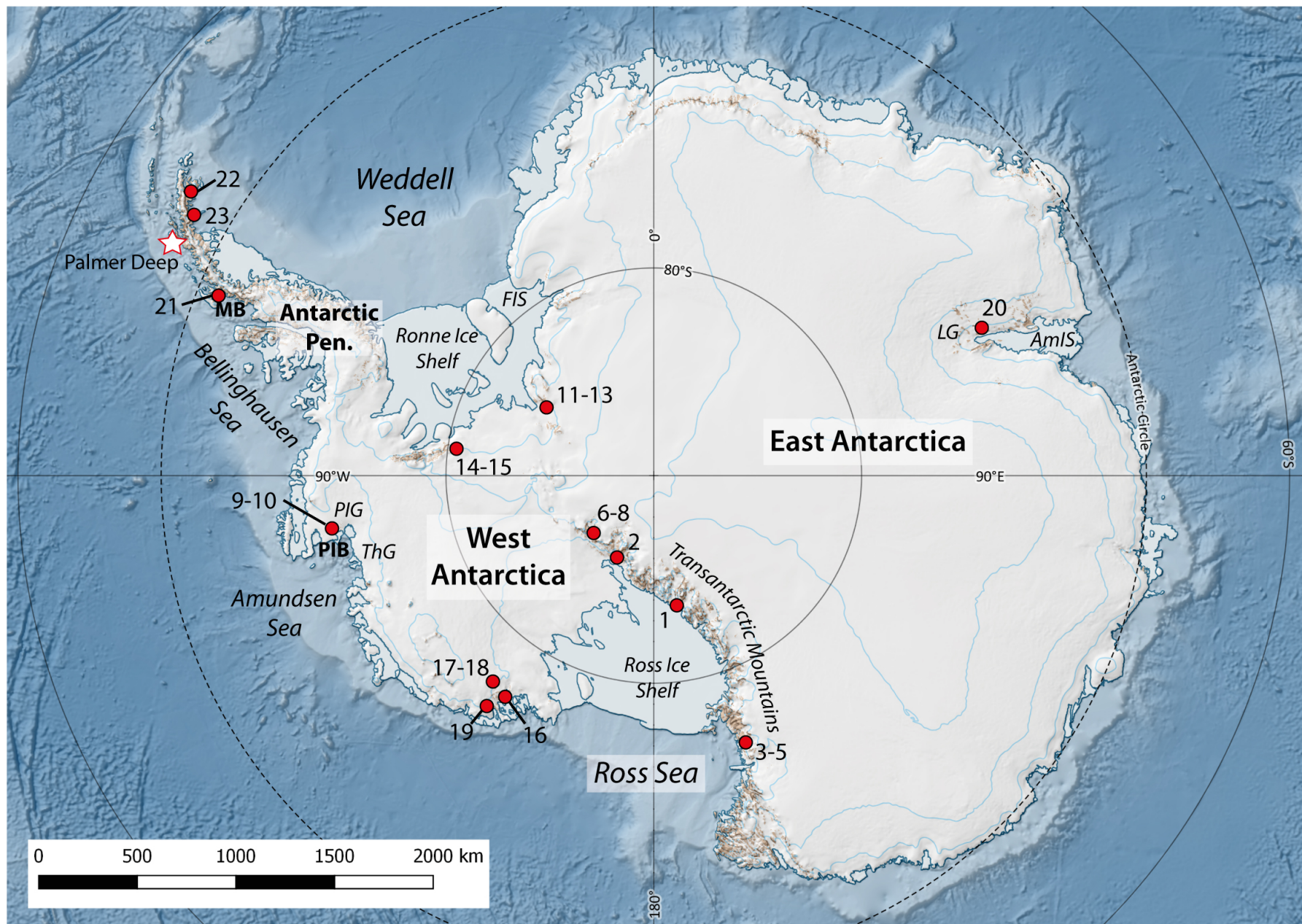
Site	ID No.	MC 95% Onset		MC 95% End		Bayesian Onset 95%		Bayesian End 95%	
		Mid-range	+/-	Mid-range	+/-	Mid-range	+/-	Mid-range	+/-
Mount Hope	1	12200	900	7600	700	12400	1200	7200	800
Mount Rigby/Karo	2	12200	1200	-100	1000	11500	1700	100	100
Mount Suess/Gondola Upper	3	6800	700	5400	800	7100	1000	4900	1300
Gondola Mid-lower	4	7000	600	6300	600	6900	600	6100	800
Low Ridge (all)	5	7600	1100	-200	1100	6900	1100	200	200
Low Ridge (subset n=5)	5a	6600	500	6000	500	6900	1100	5200	1500
Reedy Glacier (Quartz Hills)	6	10000	1200	6800	1400	10300	1400	6600	100
Reedy Glacier (Pip's Peak)	7	7400	300	7000	300	10300	3200	300	300
Reedy Glacier (Cohen's Nunatak)	8	8600	2000	1400	1700	10300	3800	900	900
Maish Nunatak	9	7200	300	6800	400	7400	700	6700	700
Mount Moses (all)	10	7400	700	5400	700	8600	1000	5300	1300
Mount Moses (subset n= 3)	10a	7100	200	6900	200	8600	1000	7200	800
Williams Hills	11	8800	600	4300	5100	7900	900	4700	600
Thomas Hills	12	6800	500	6500	500	6900	500	6600	500
Mount Harper/Bragg	13	5800	1300	2400	1700	7200	1600	1800	1100
Marble Hills	14	9400	1000	5300	800	10200	1600	4200	1400
Patriot Hills	15	7400	1100	3100	1000	7400	2500	3800	500
Mount Rea	16	3300	400	2200	400	4100	1000	1700	700
Mount Darling	17	9200	200	3400	300	12100	3900	2100	2100
Mount Valkenburg	18	6600	500	3100	500	10600	4800	1900	1900
Fosdick Mountains	19	5100	100	2200	100	6200	2000	1300	1300
Mount Stinear	20	11400	1200	10300	800	11300	1100	9900	1200
Porquoi-Pas Island	21	11100	800	10300	800	11300	1100	10200	1200
James Ross Island	22	9700	1900	6600	1800	9100	1400	7100	1900
Sjorden-Boydell	23	7600	400	3400	400	8100	1400	2500	1300

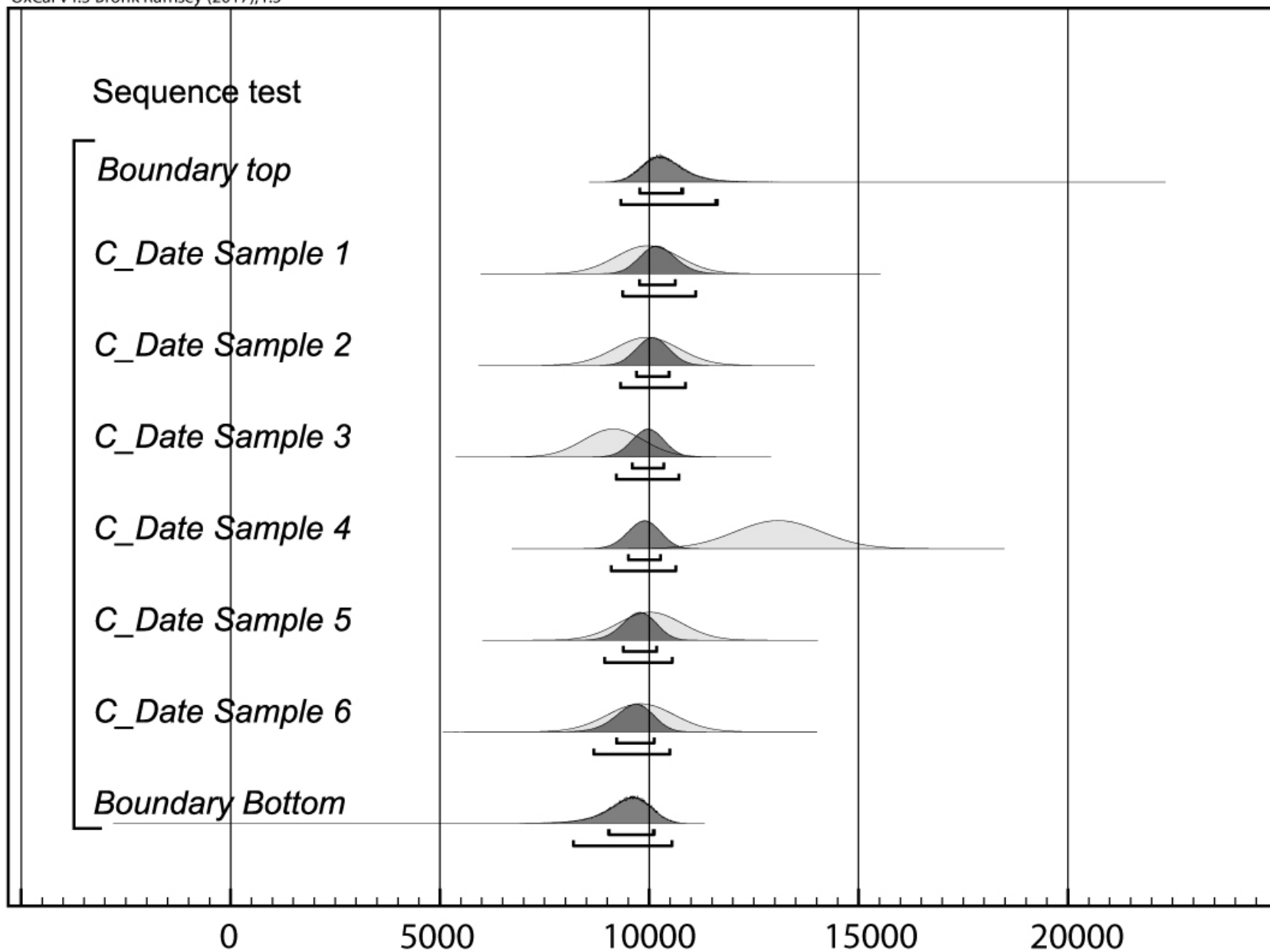
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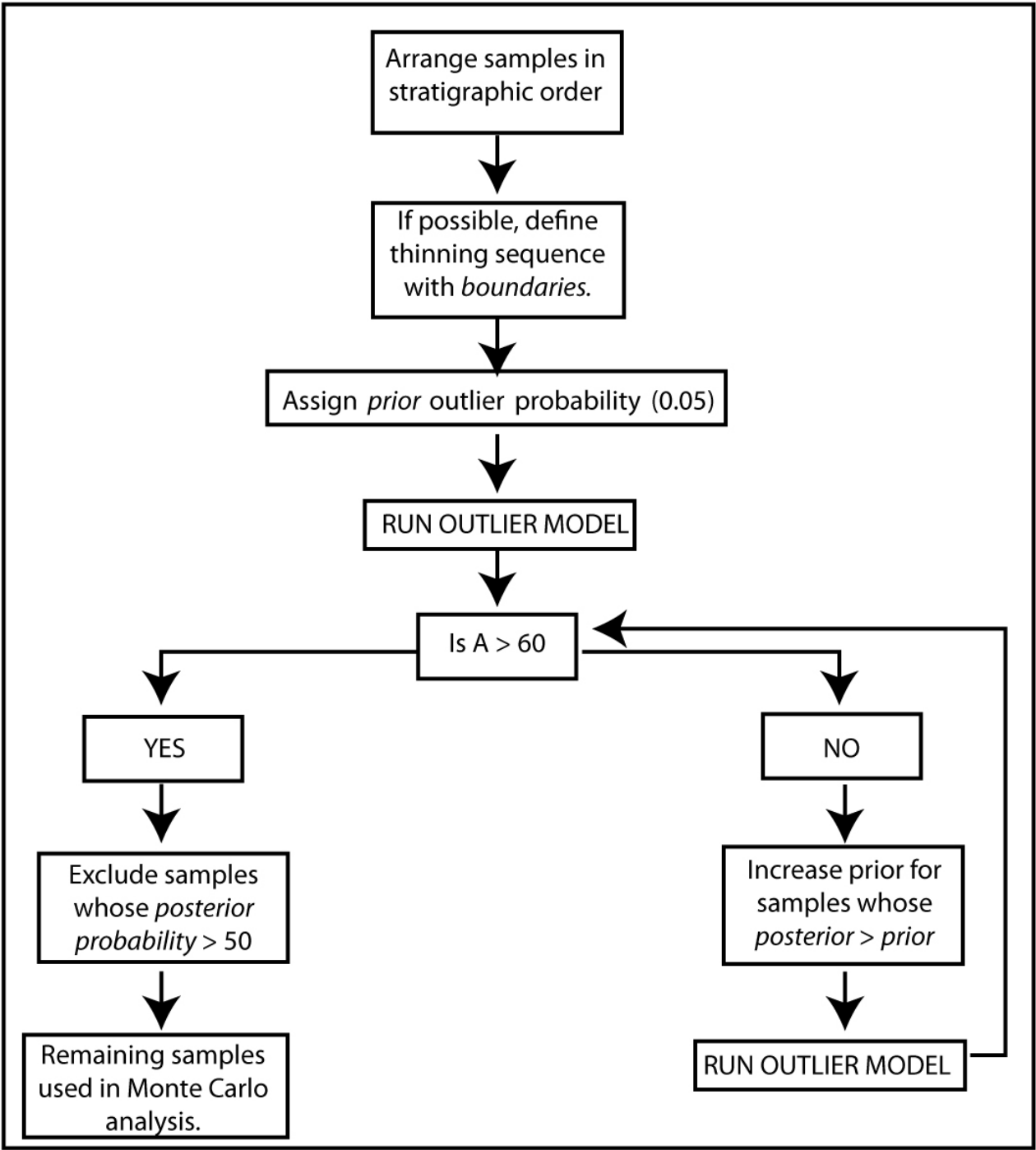
1007 Table 6. Alternate thinning rates from Monte Carlo analysis for sites where Bayesian outlier detection resulted in exclusion of 'young' erratics.

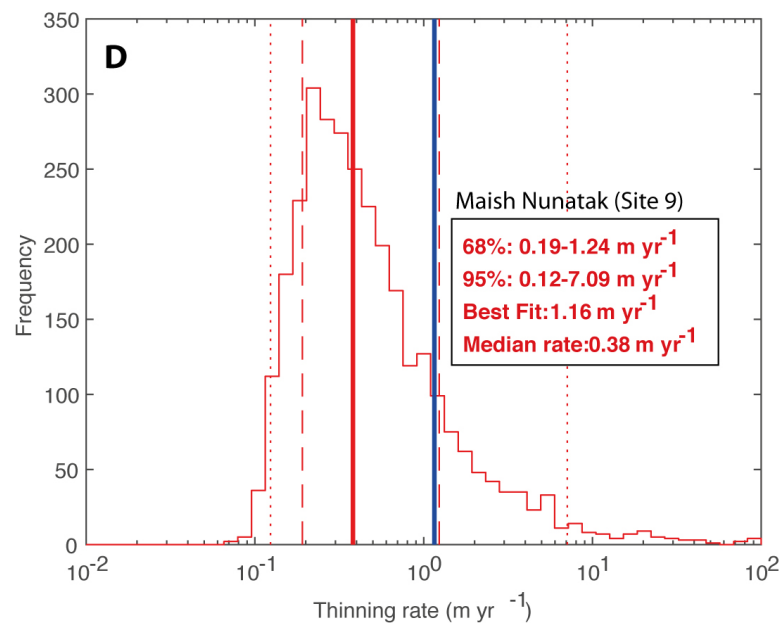
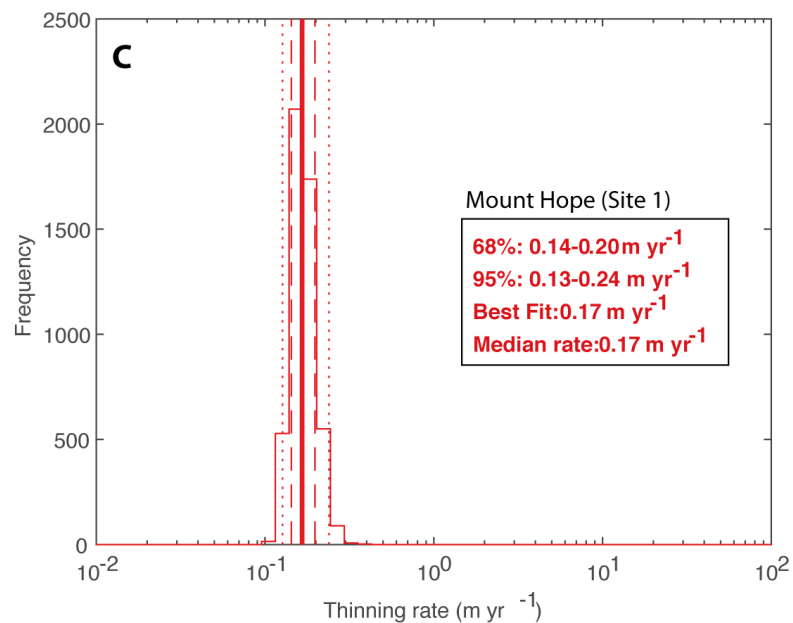
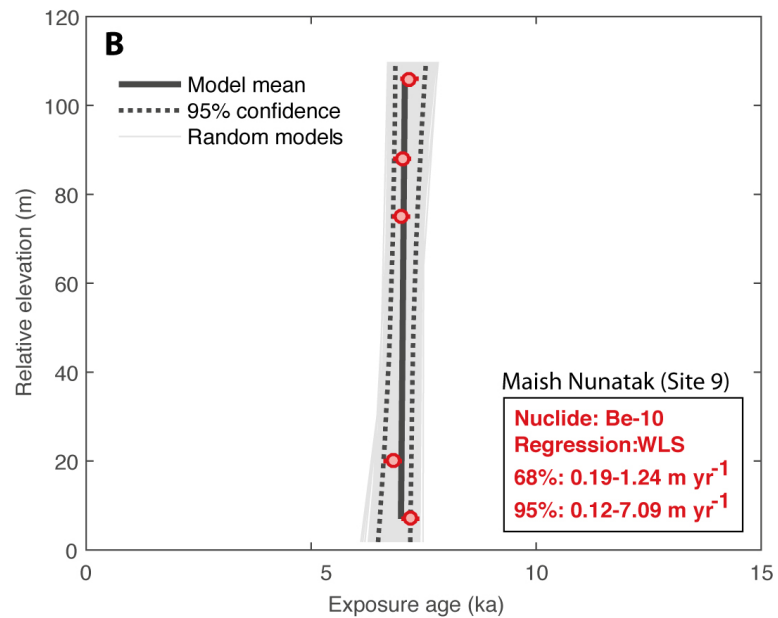
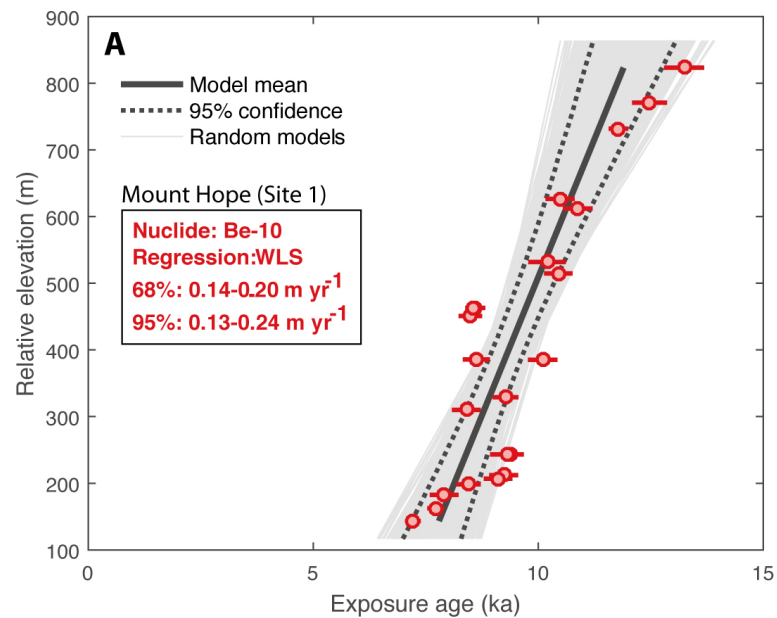
Site	Total samples in profile	Young sample(s) excluded	Alternate 68% range (m yr ⁻¹)	Alternate 95% range (m yr ⁻¹)	Alt. best fit (m yr ⁻¹)	Alt. median (m yr ⁻¹)
Low Ridge	10	CC93	0.03-0.19	0.02-0.90	0.19	0.16
Williams Hills	17	WIL-4	0.09-0.15	0.08-0.21	0.12	0.12
Mount Harper/Bragg	12	HAR-3	0.05-0.11	0.04-0.25	0.07	0.07
Marble Hills	28	MH12-16	0.08-0.15	0.06-0.25	0.10	0.10
Patriot Hills	11	PH12-28	0.06-0.14	0.05-0.34	0.09	0.09
James Ross Island	7	JOH-04	0.06-0.26	0.04-1.36	0.12	0.10

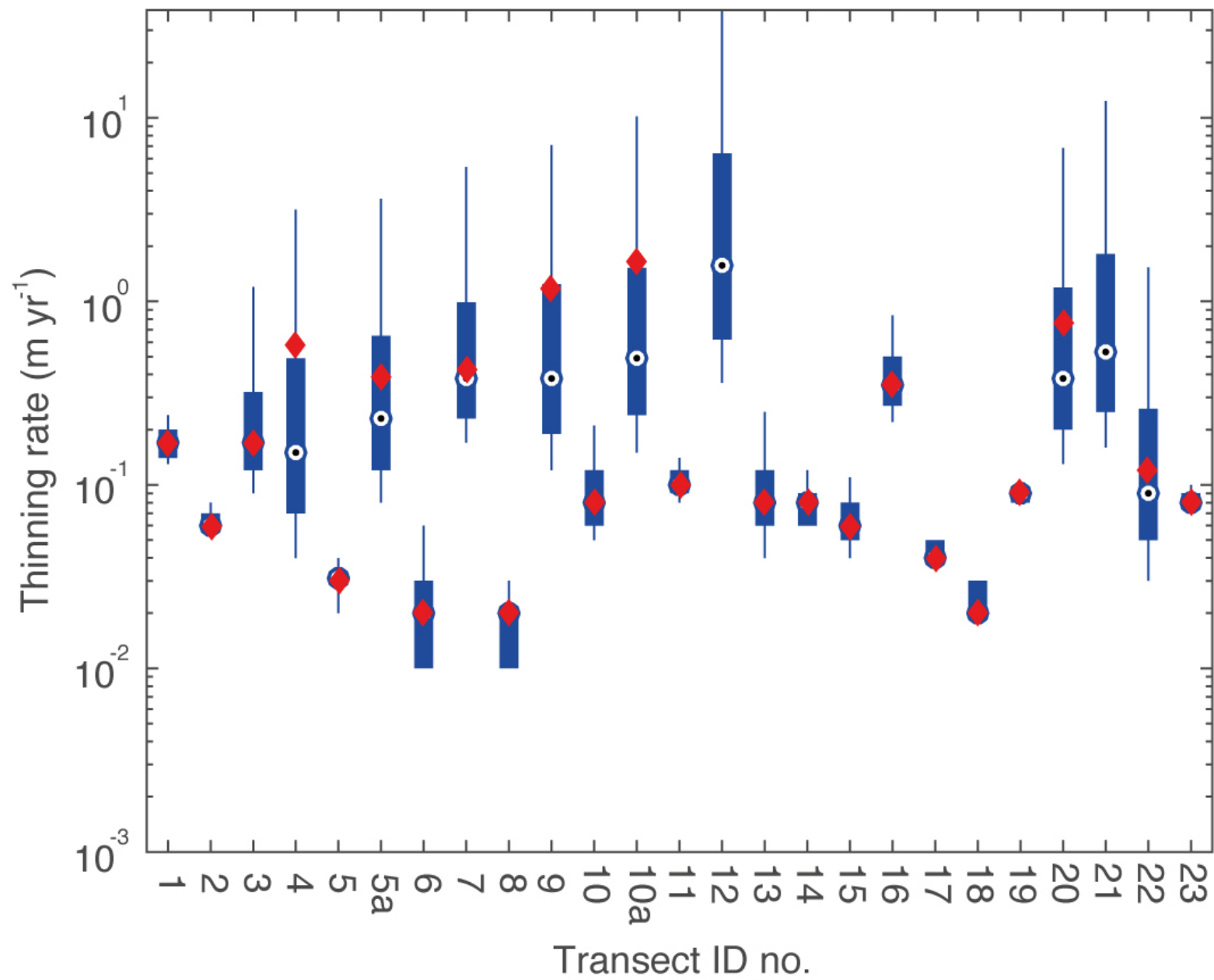


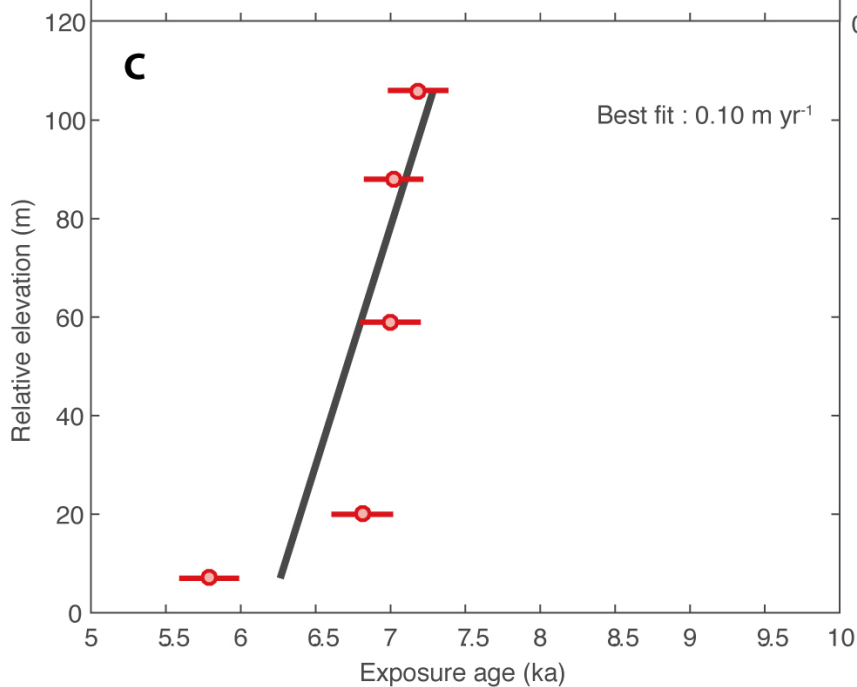
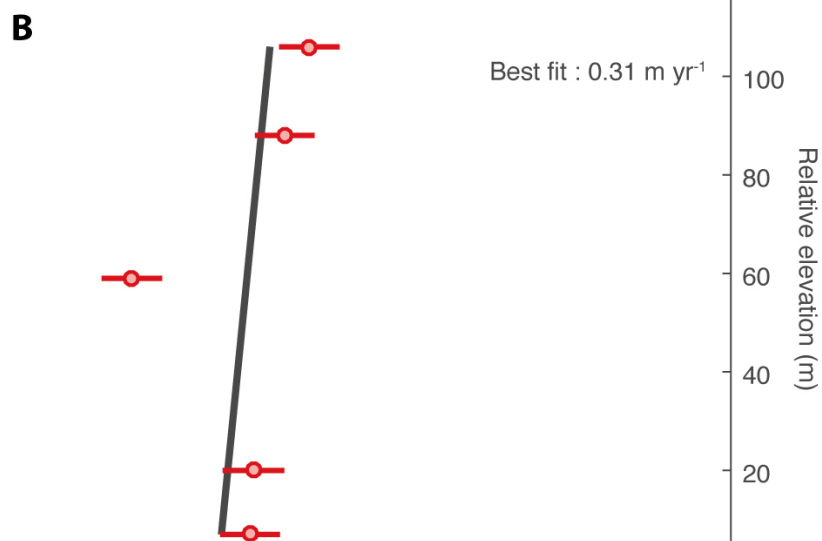
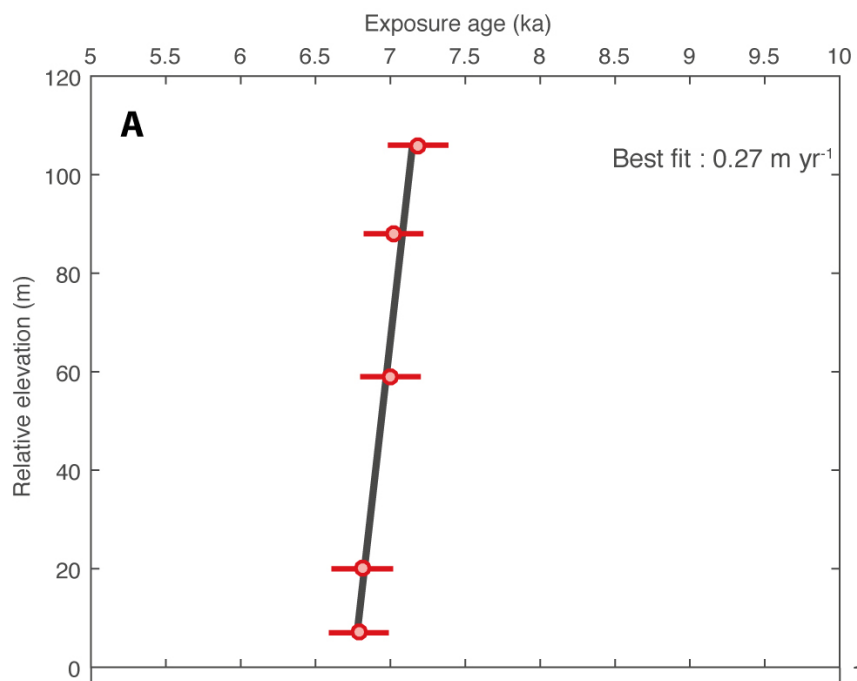


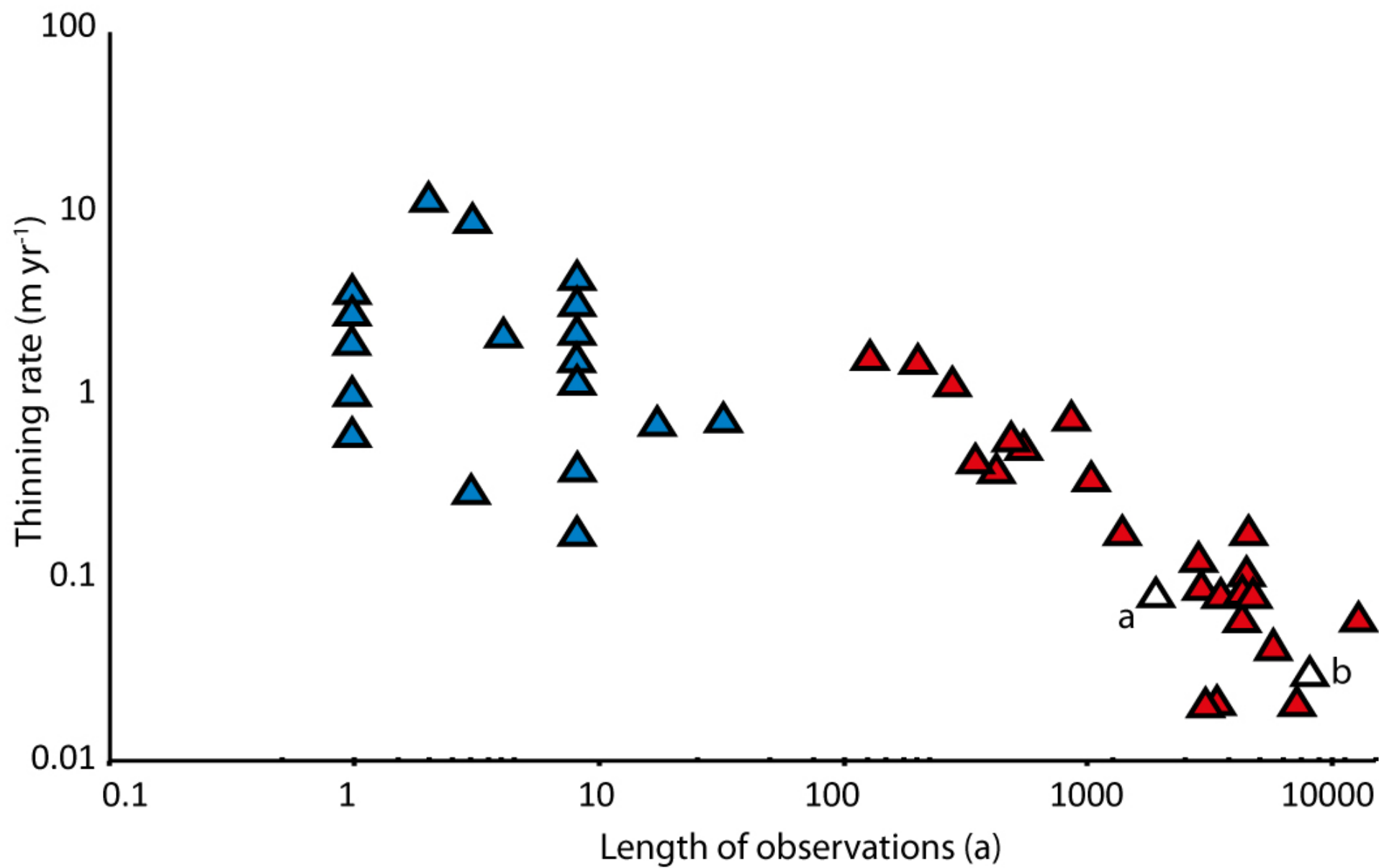


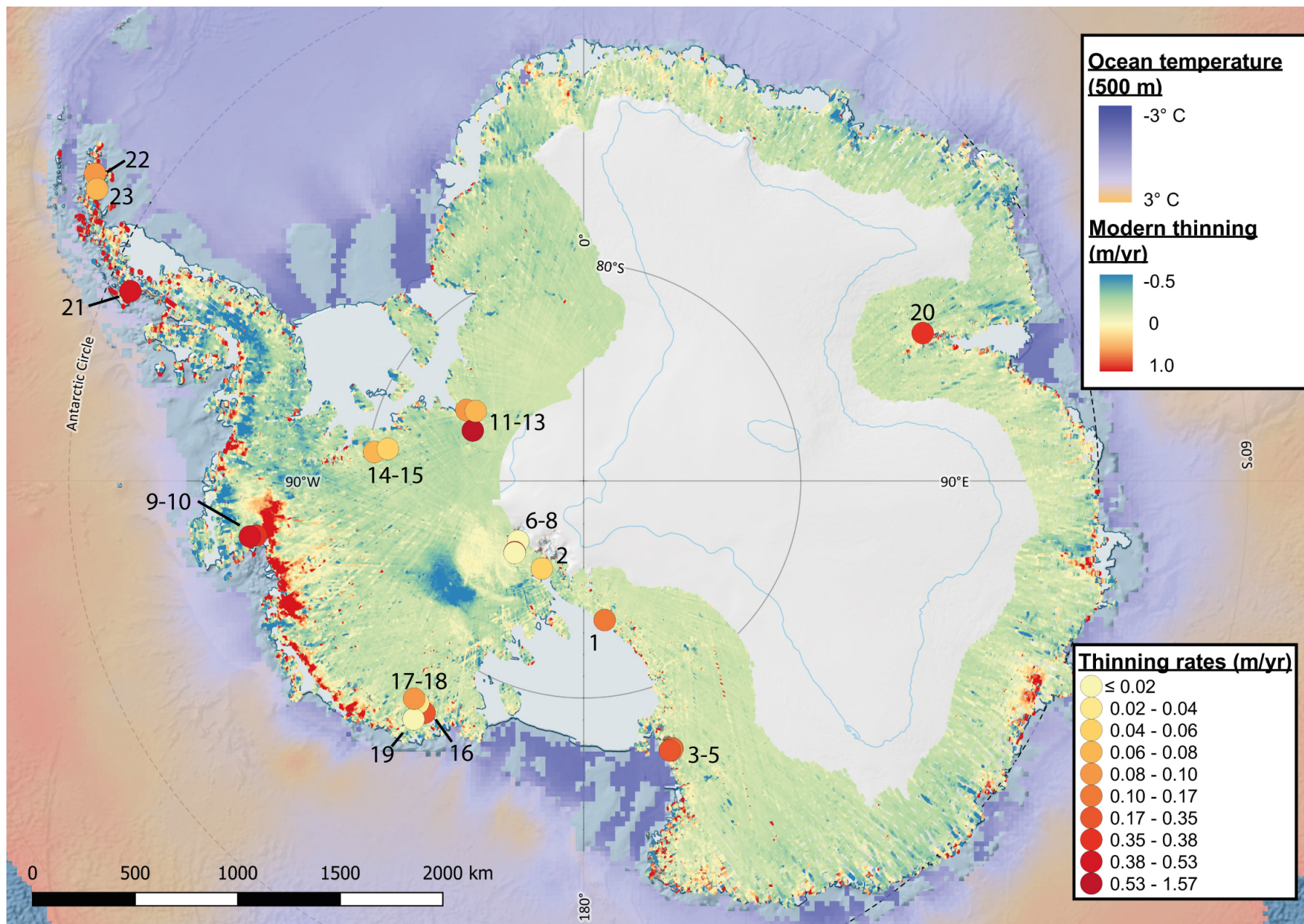


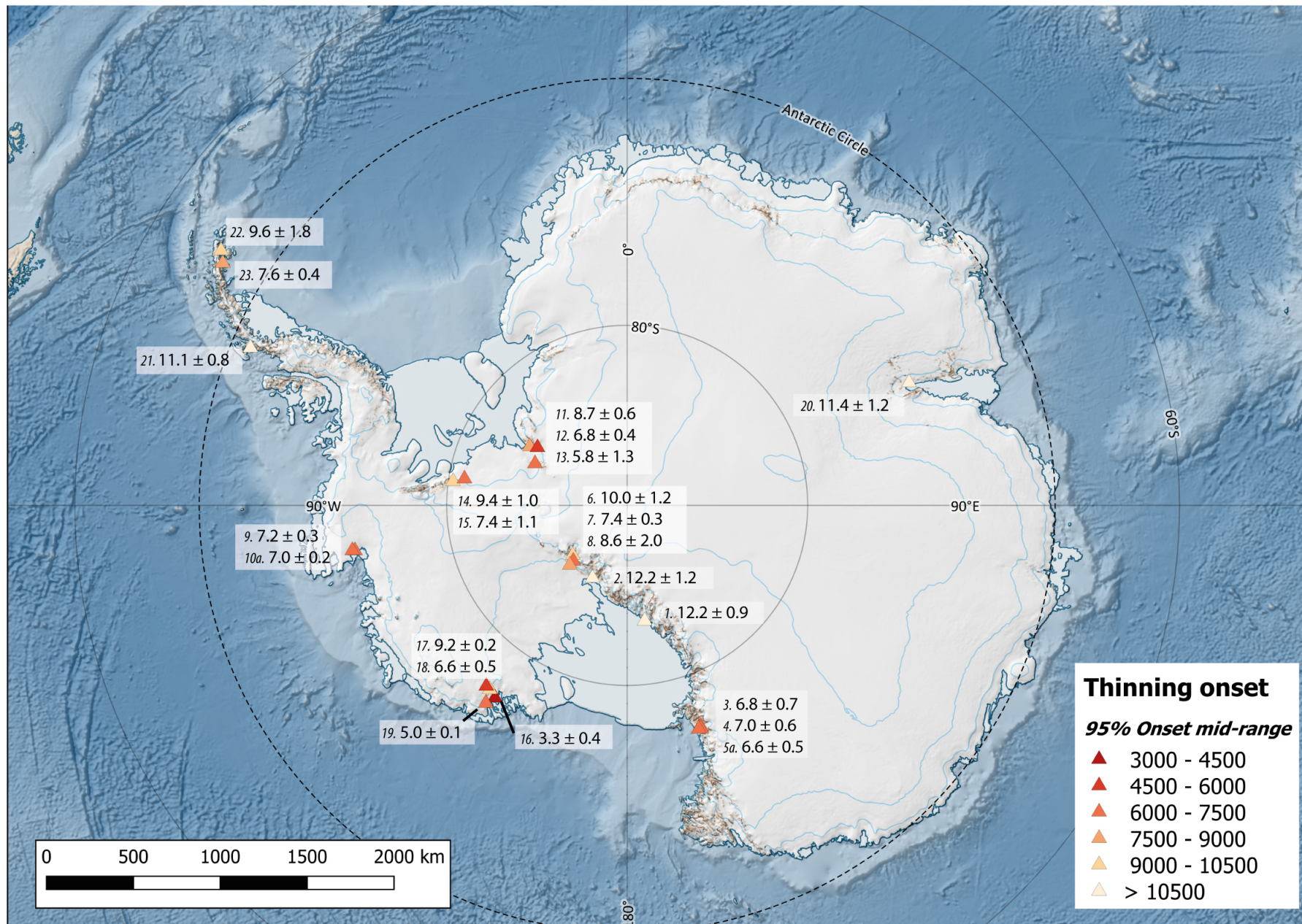


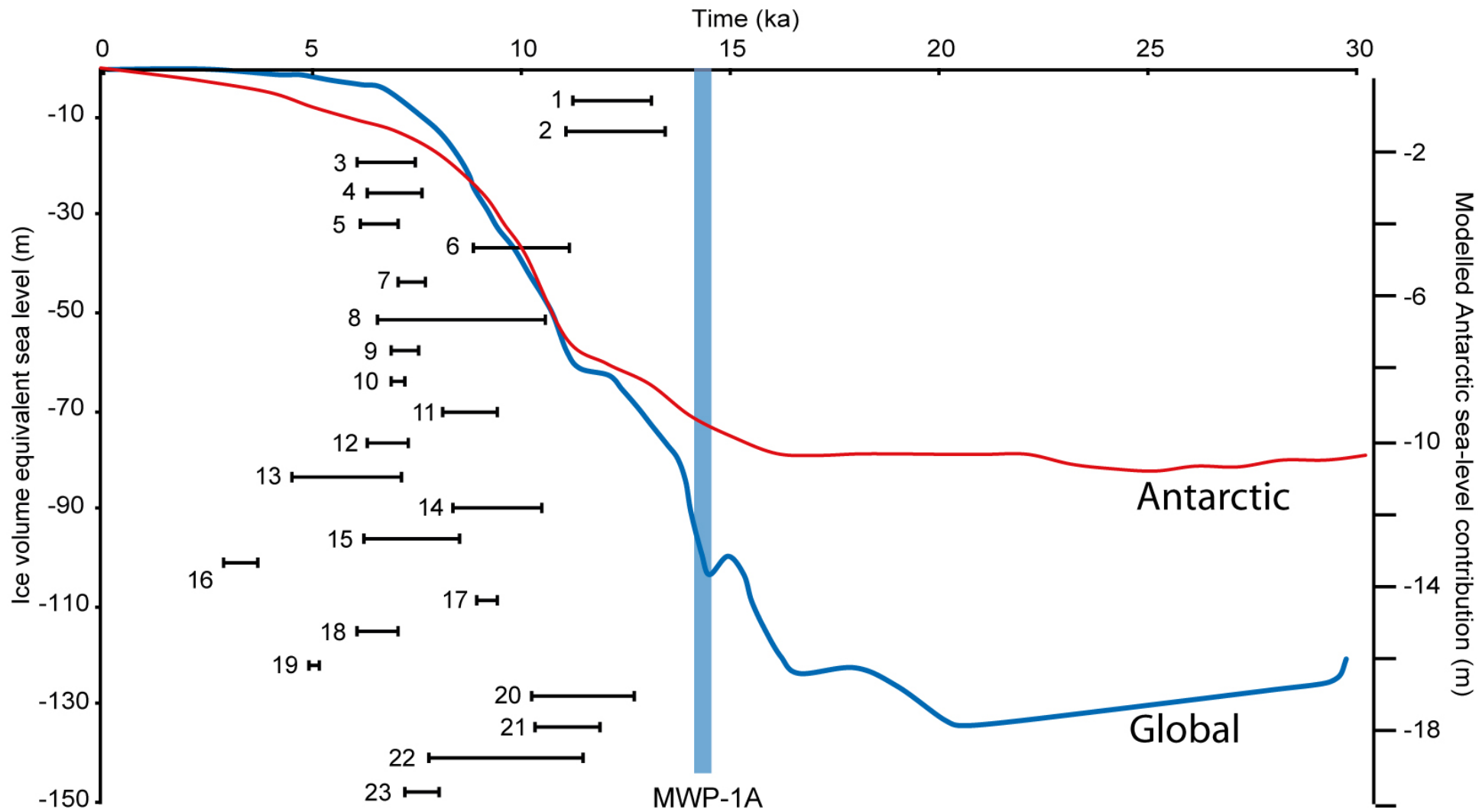












Mt Hope

OxCal v4.3.2 Bronk Ramsey (2017); r:5

Sequence test

Boundary top

C_Date 10BDM060HOP

C_Date 10BDM062HOP

Phase 732m

C_Date 10BDM064HOP

C_Date 07SCT185HOP

C_Date 10BDM067HOP

C_Date 10BDM068HOP

C_Date 10BDM072HOP

C_Date 10BDM074HOP

Phase 462m

C_Date 07SCT189HOP

C_Date 07SCT188HOP

Phase 451m

C_Date 10BDM075HOP

C_Date 10BDM077HOP

Phase 385m

C_Date 10BDM054HOP

C_Date 10BDM056HOP

C_Date 10BDM052HOP

C_Date 10BDM050HOP

Phase 242m

C_Date 07SCT198HOP

C_Date 07SCT197HOP

C_Date 10BDM079HOP

C_Date 10BDM080HOP

C_Date 10BDM082HOP

C_Date 10BDM083HOP

C_Date 07SCT196HOP

C_Date 10BDM046HOP

C_Date 07SCT195HOP

C_Date 07SCT194HOP

Boundary z

C_Date 07SCT192HOP

C_Date 07SCT190HOP

Boundary Bottom

Outlier

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100

25000

20000

15000

10000

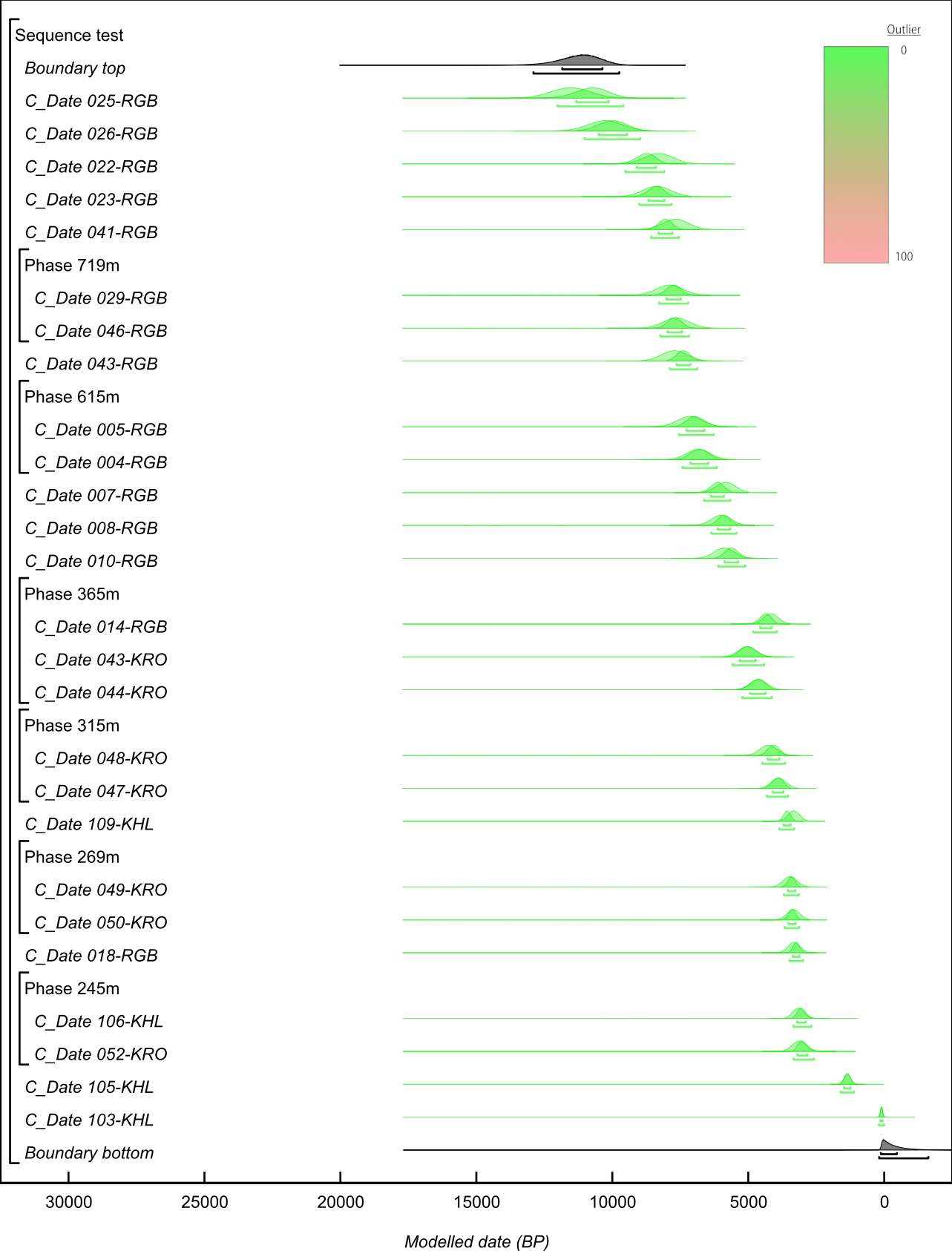
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Modelled date (BP)

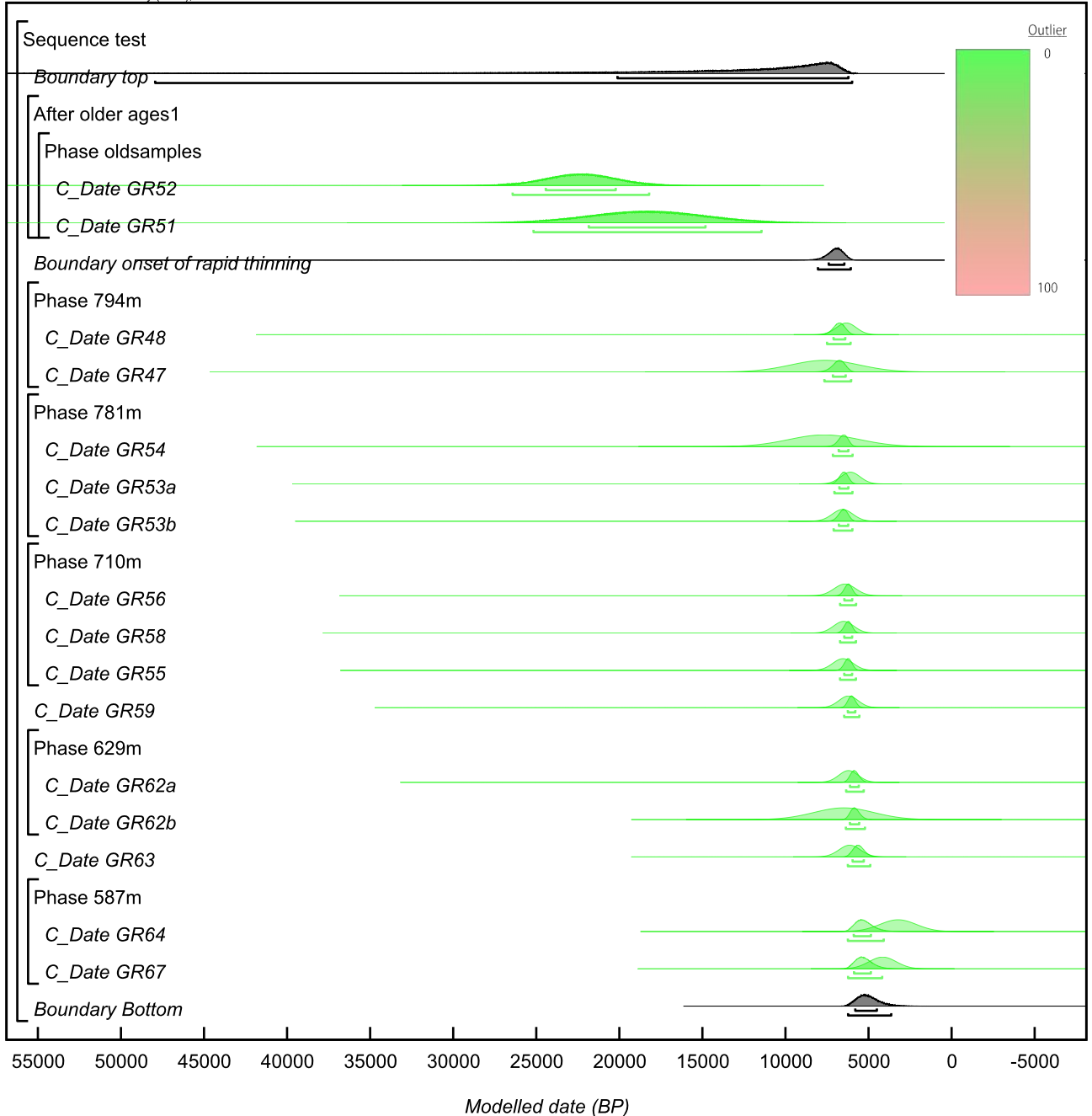
Mt Rigby-Karo

OxCal v4.3.2 Bronk Ramsey (2017); r:5



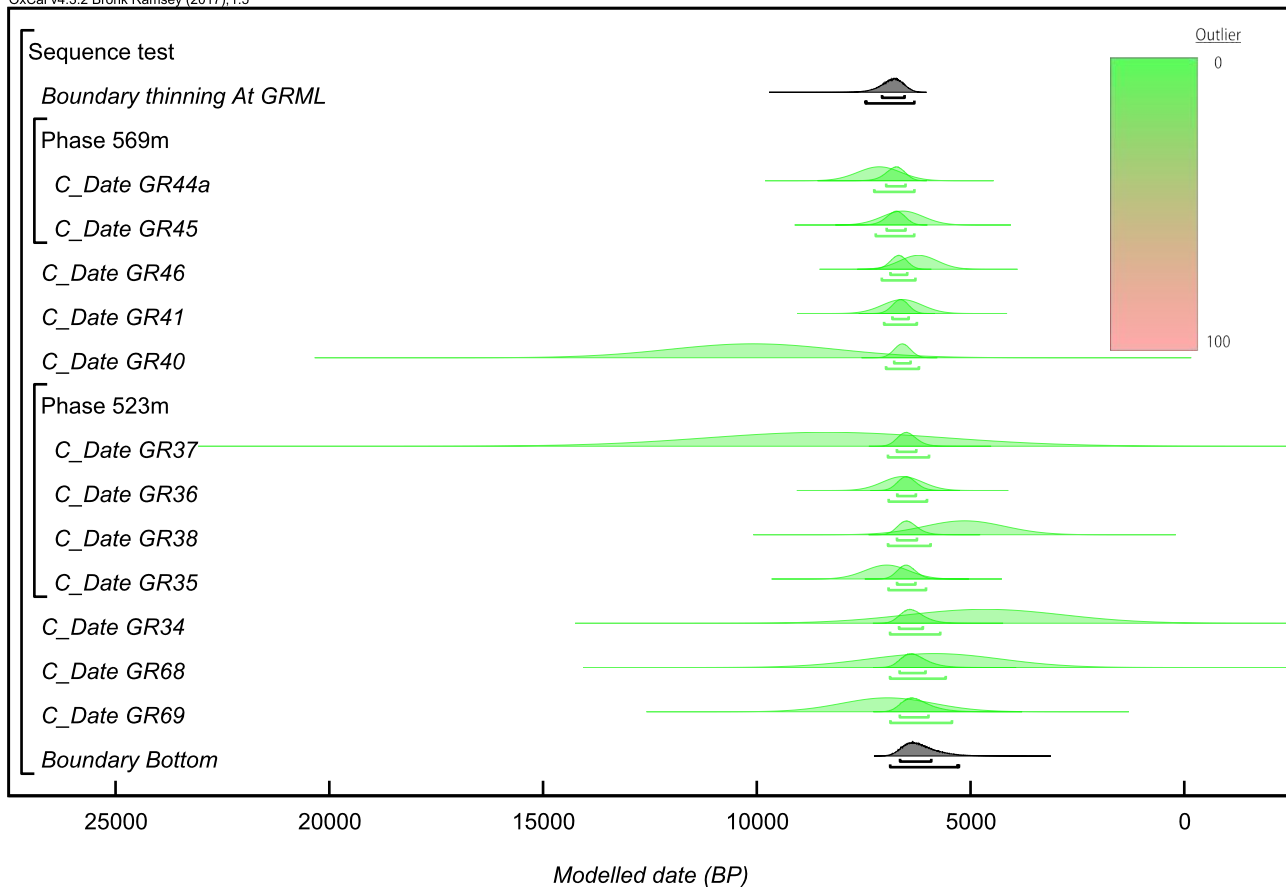
Mt Suess/Gondola Upper

OxCal v4.3.2 Bronk Ramsey (2017); r:5



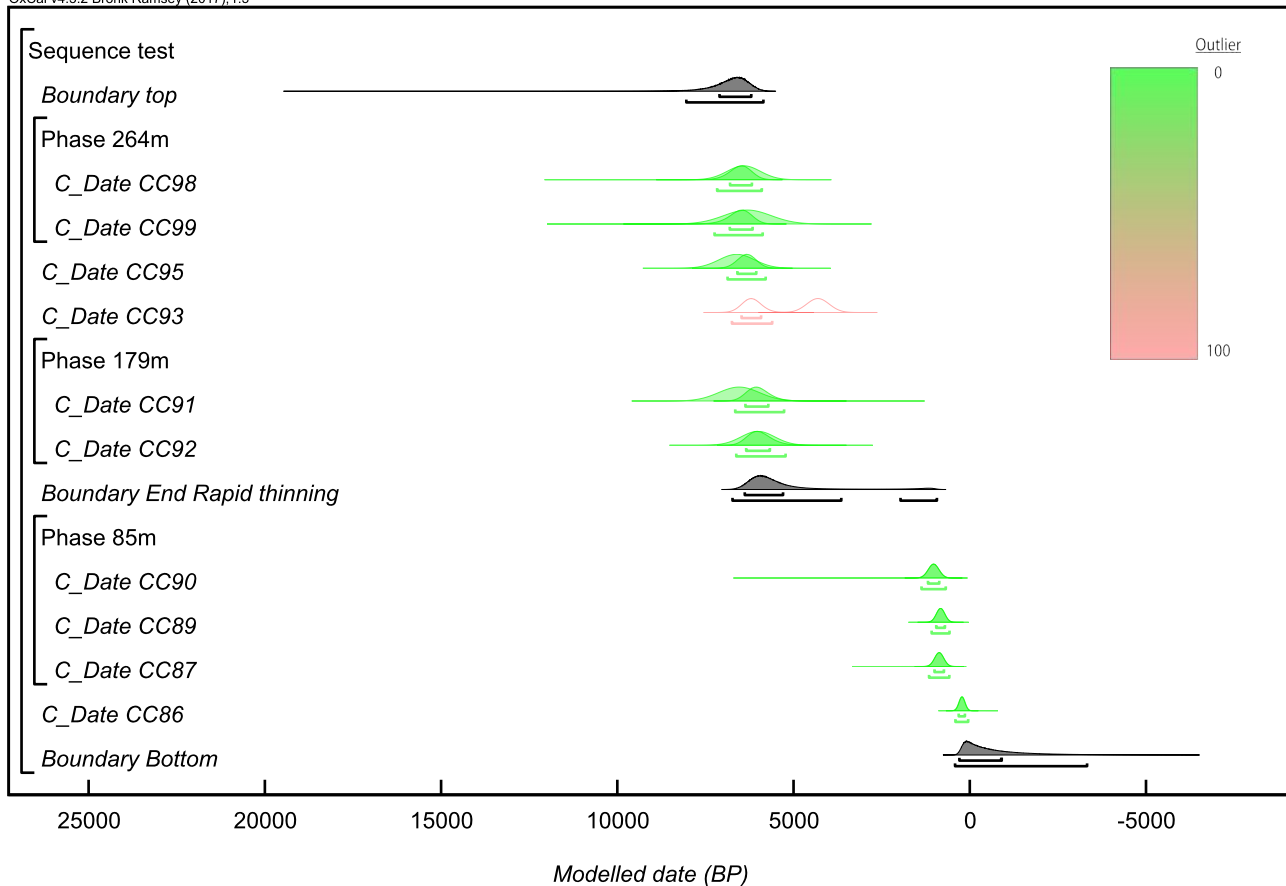
Gondola Mid-Lower

OxCal v4.3.2 Bronk Ramsey (2017); r:5



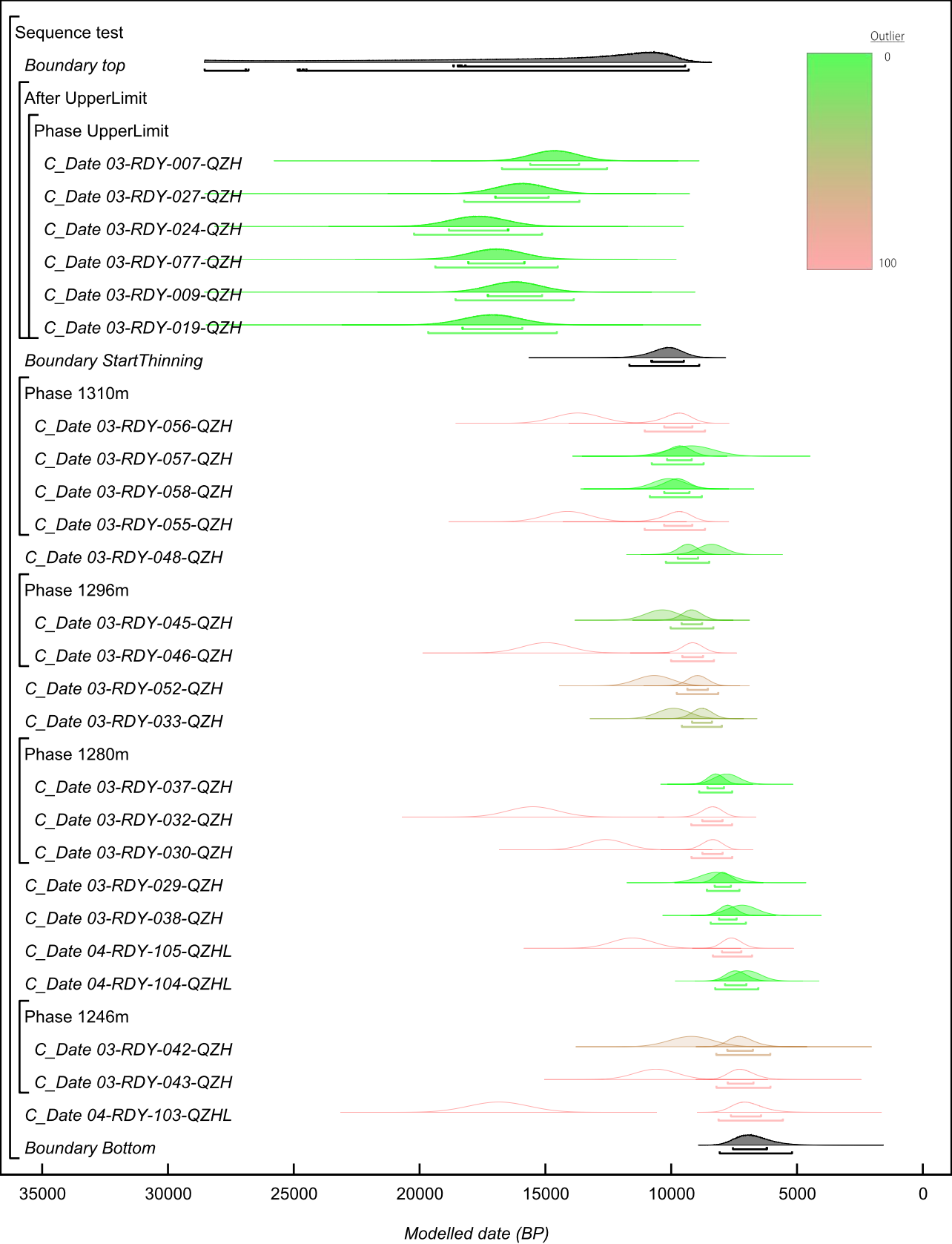
Low Ridge

OxCal v4.3.2 Bronk Ramsey (2017); r:5



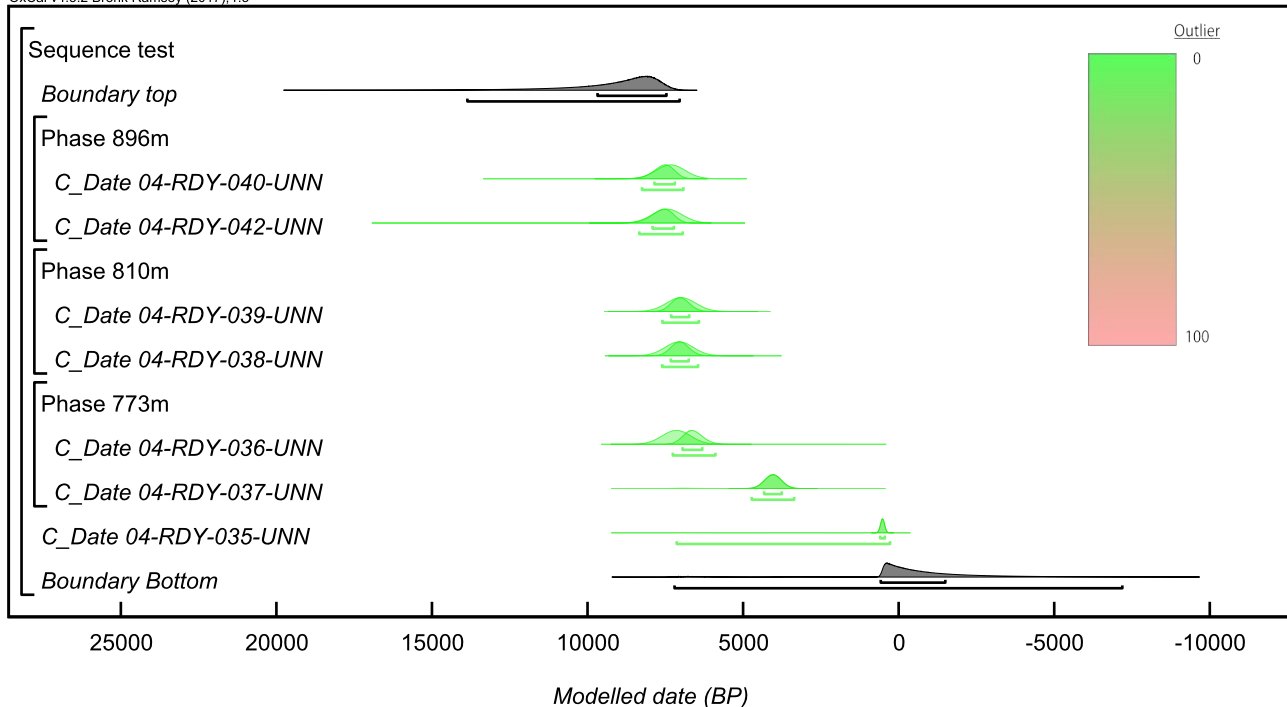
Reedy Glacier - Quartz Hills

OxCal v4.3.2 Bronk Ramsey (2017); r:5



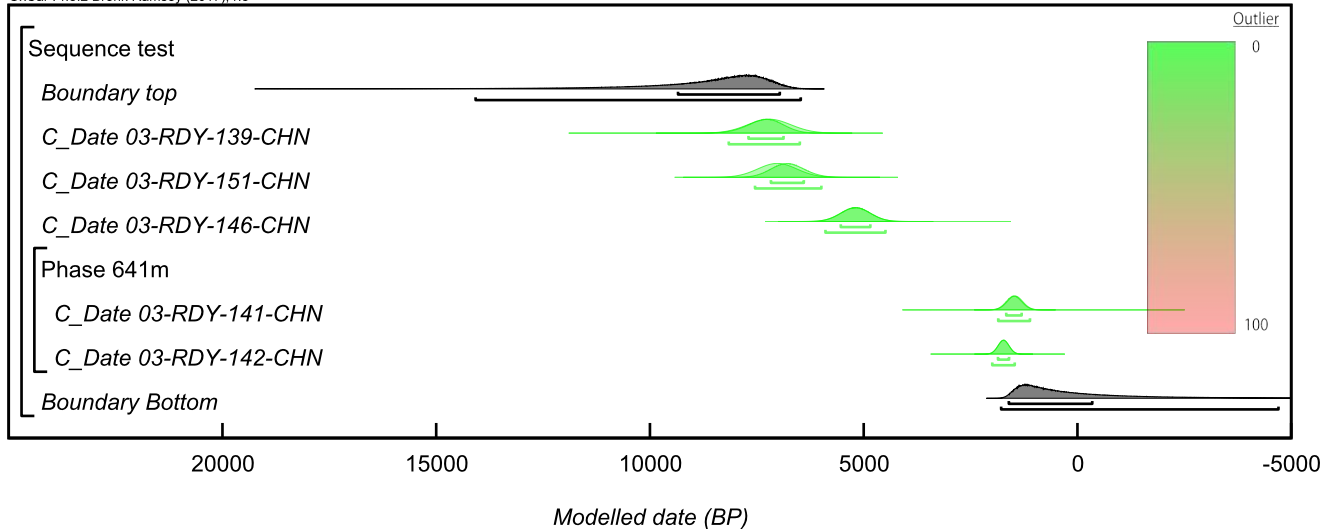
Pip's Peak

OxCal v4.3.2 Bronk Ramsey (2017); r:5



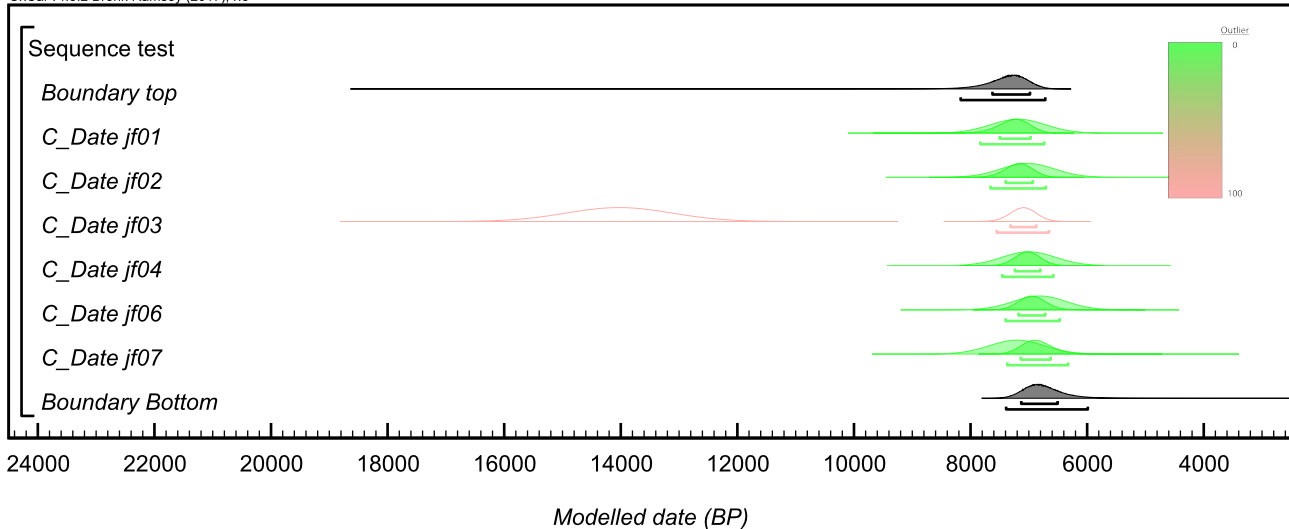
Cohen's Nunatak

OxCal v4.3.2 Bronk Ramsey (2017); r:5



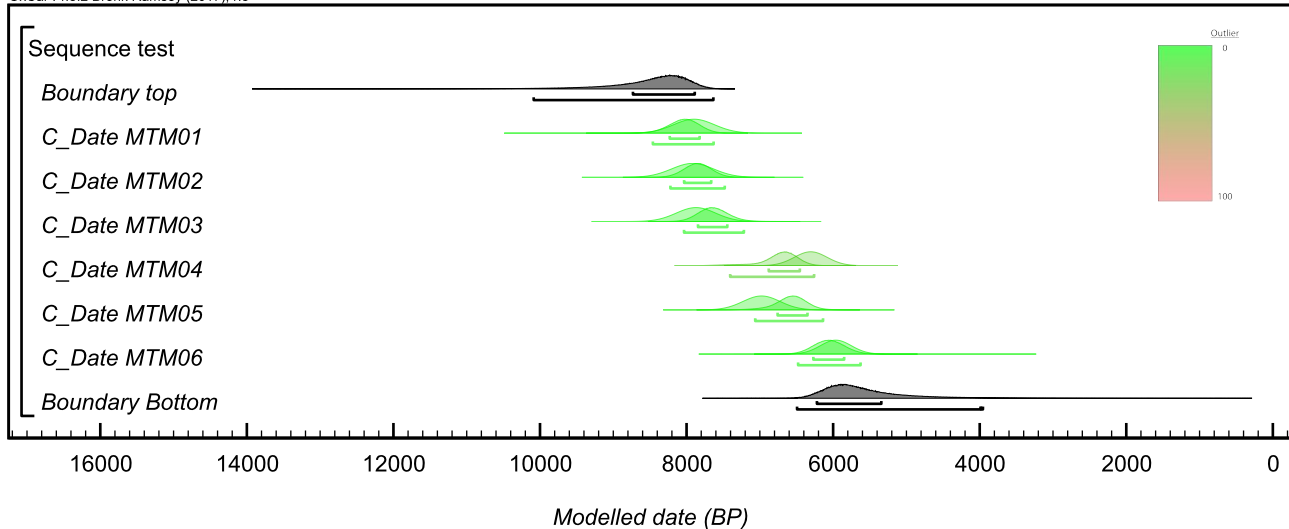
Maish Nunatak

OxCal v4.3.2 Bronk Ramsey (2017); r:5



Mt Moses

OxCal v4.3.2 Bronk Ramsey (2017); r:5



Williams Hills

OxCal v4.3.2 Bronk Ramsey (2017); r:5

Sequence test

Boundary top

C_Date B2016-WIL-26

C_Date 123-HBS

C_Date 073-CRK

C_Date 124-LNK

C_Date 126-LNK

Phase 295m

C_Date B2016-WIL-32

C_Date B2016-WIL-33

Phase 285m

C_Date B2016-WIL-18

C_Date 075-CRK

C_Date B2016-WIL-19

C_Date B2016-WIL-20

Phase 255 m

C_Date B2016-WIL-21

C_Date 128-LNK

C_Date 129-LNK

Phase 230m

C_Date B2016-WIL-6

C_Date B2016-WIL-5

C_Date 090-CRK

C_Date B2016-WIL-4

C_Date 095-CRK

Phase 172m

C_Date B2016-WIL-3

C_Date B2016-WIL-8

C_Date 099-CRK

C_Date B2016-WIL-1

C_Date B2016-WIL-13

C_Date B2016-WIL-28

C_Date B2016-WIL-15

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C_Date B2016-WIL-17

Boundary bottom

Outlier

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16000

14000

12000

10000

8000

6000

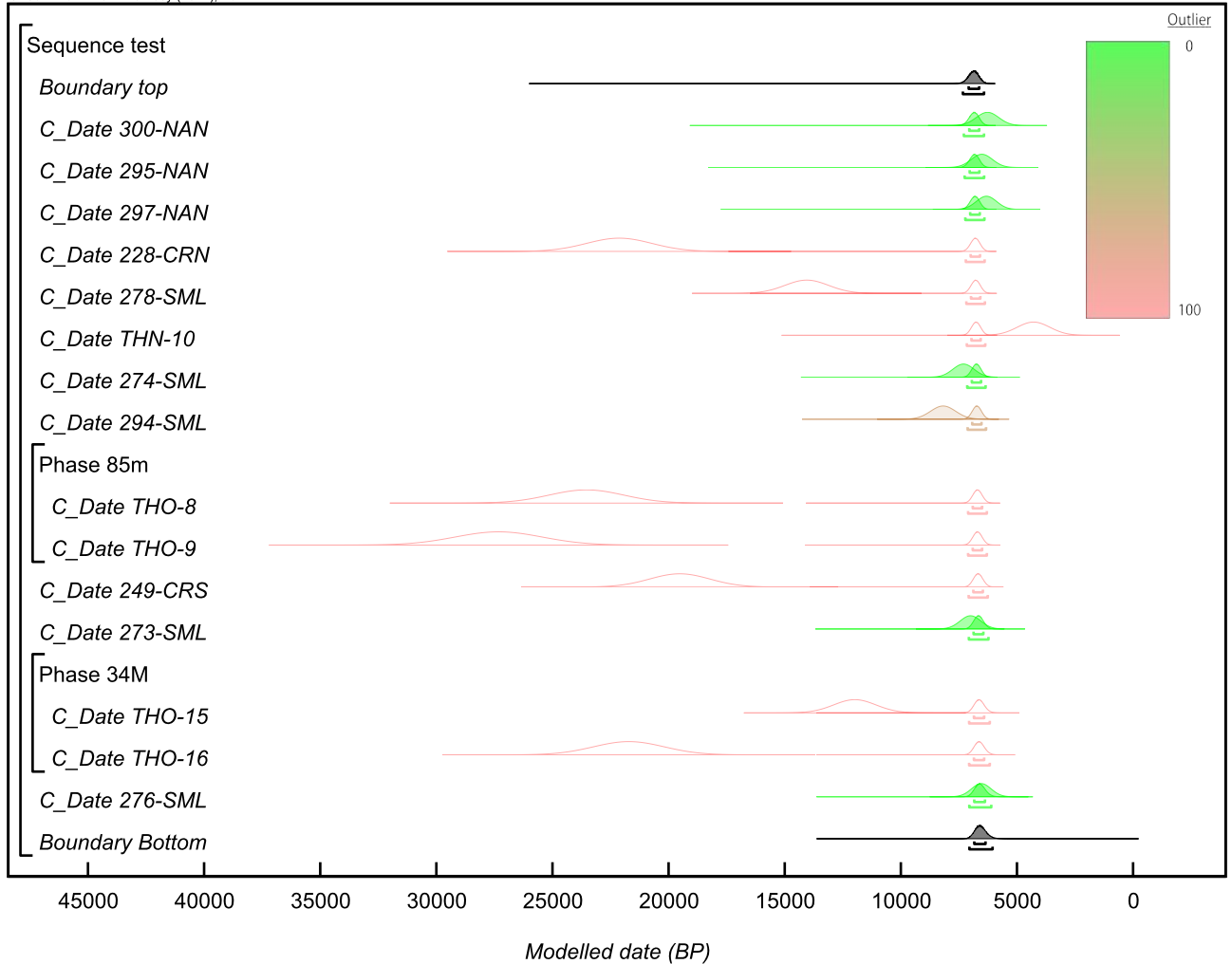
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2000

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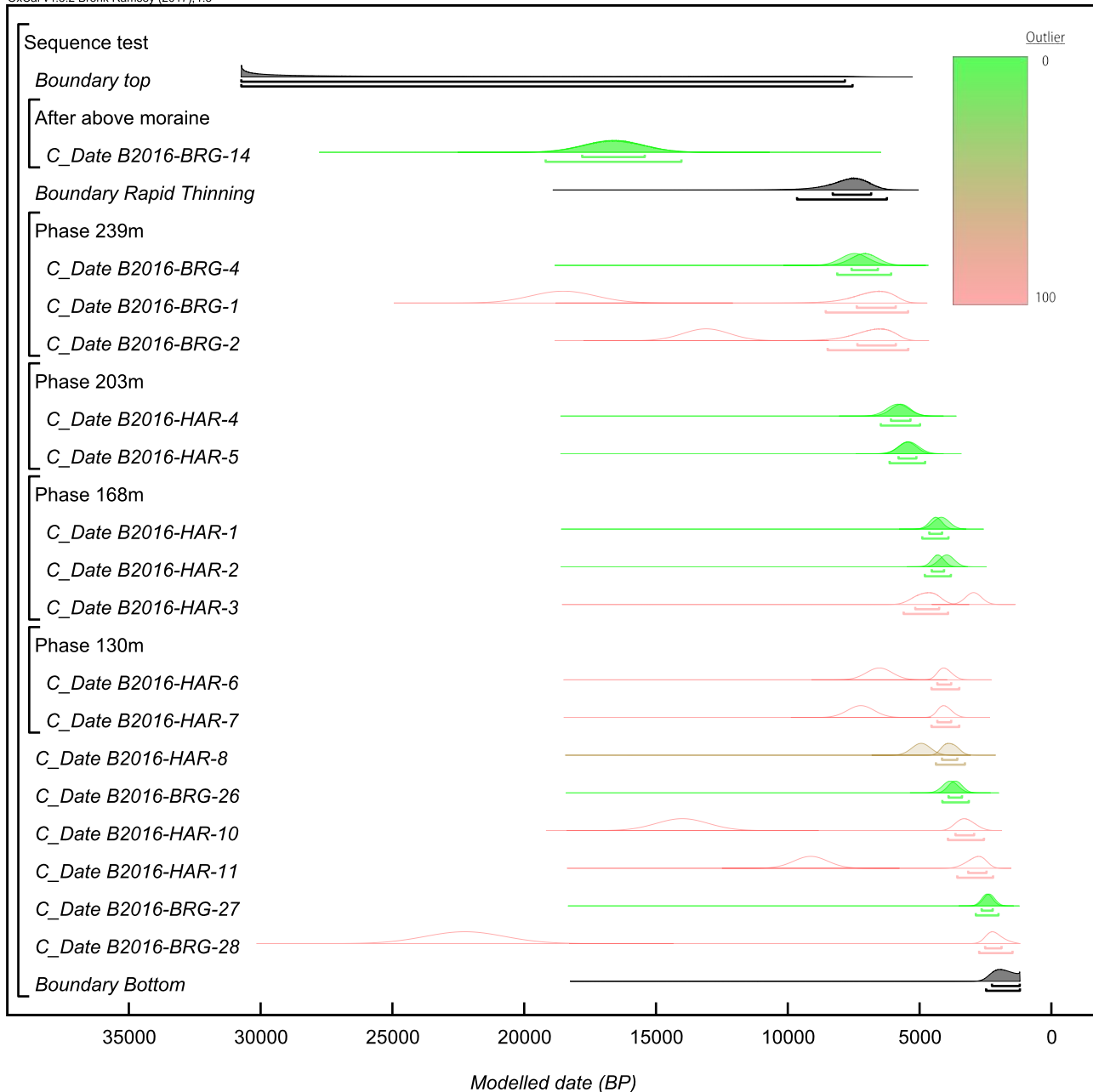
Thomas Hills

OxCal v4.3.2 Bronk Ramsey (2017); r:5



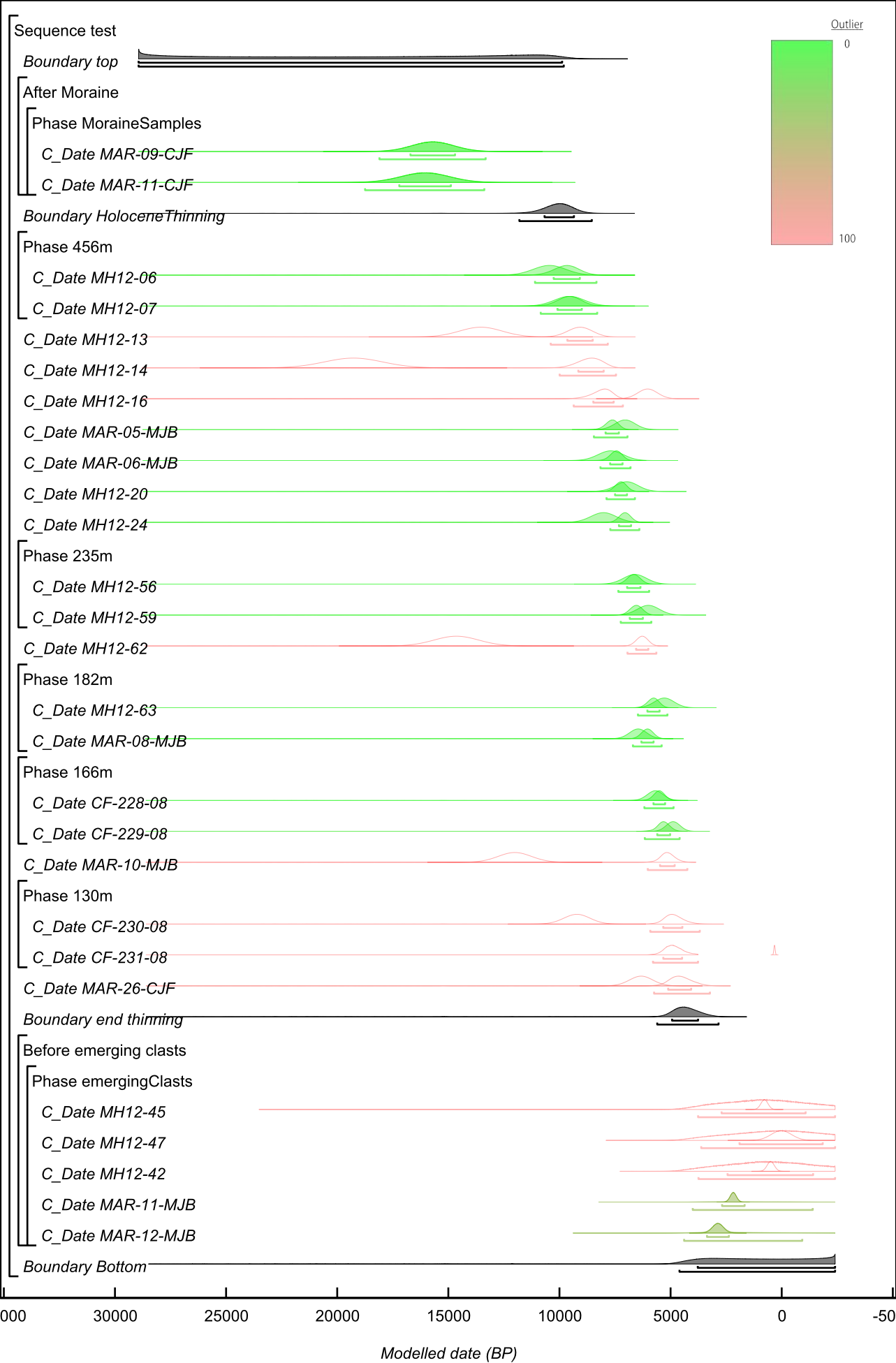
Mt Harper-Bragg

OxCal v4.3.2 Bronk Ramsey (2017); r:5



Marble Hill's

OxCal v4.3.2 Bronk Ramsey (2017); r:5



Patriot Hills

OxCal v4.3.2 Bronk Ramsey (2017); r:5

Sequence test

Boundary top

C_Date PAT-01-MJB

C_Date PH12-28

C_Date PAT-03-MJB

C_Date PH12-113

C_Date PAT-04-MJB

C_Date PH12-114

Phase 137m

C_Date PH12-53

C_Date PH12-54

C_Date PH12-35

C_Date PH12-57

C_Date PAT-05-MJB

Phase 104m

C_Date PH12-117

C_Date CF-31-08

C_Date PH12-40

C_Date PH12-123

C_Date CF-19-08

C_Date CF-21-08

C_Date CF-24-08

Boundary end thinning

Before emerging calsts

Phase emerging calsts

C_Date PH12-97

C_Date PH12-145

C_Date CF-02-08

C_Date CF-03-08

C_Date PH12-133

C_Date PH12-96

Boundary Bottom

Outlier

0

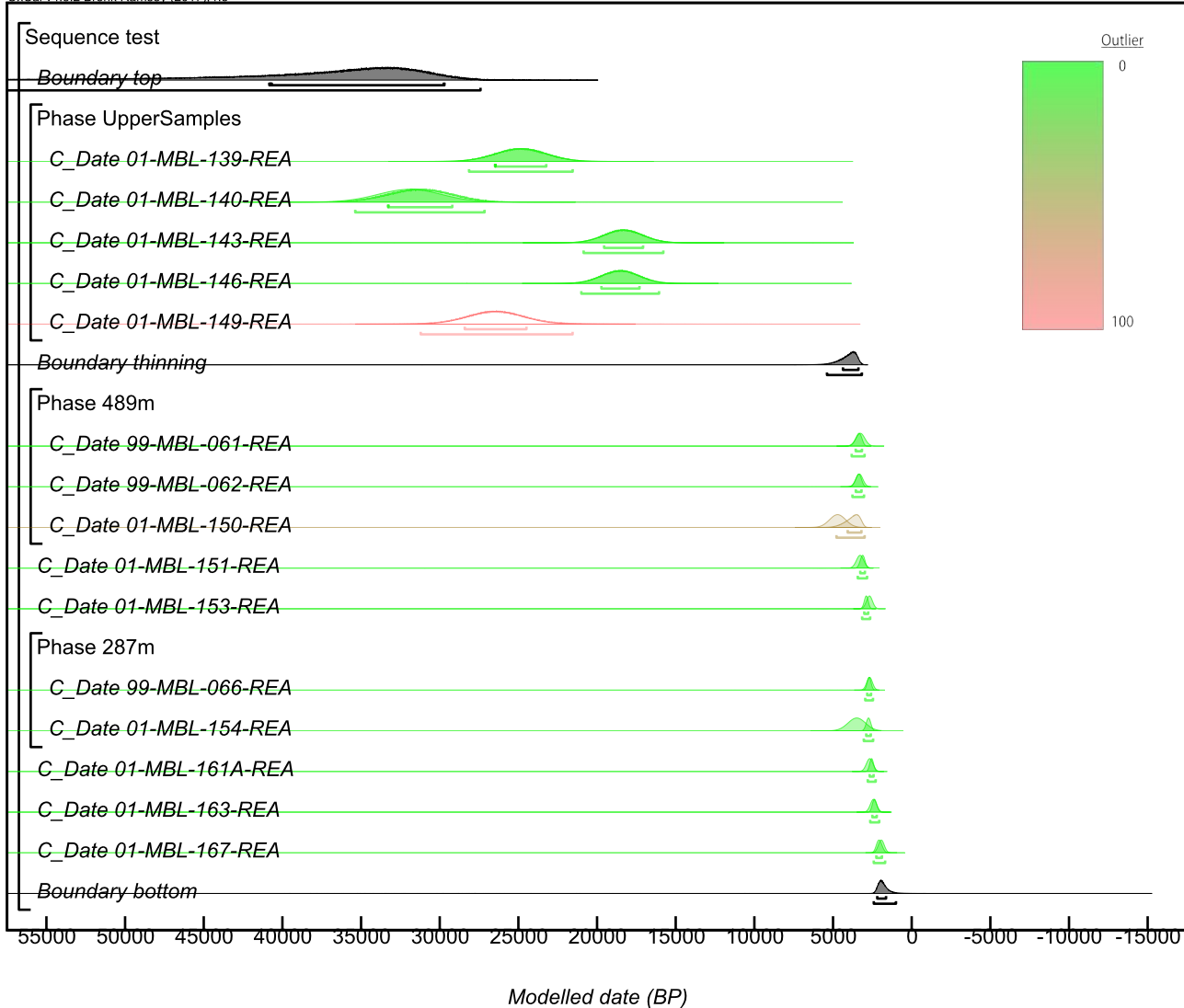
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Modelled date (BP)

Mt Rea

OxCal v4.3.2 Bronk Ramsey (2017): r.5



Mt Darling

OxCal v4.3.2 Bronk Ramsey (2017); r:5

Sequence test

Boundary top

Phase 1076m

C_Date 01-MBL-055-DAR

C_Date 01-MBL-058-DAR

C_Date 01-MBL-064-DAR

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C_Date 01-MBL-073-DAR

Boundary Bottom

Outlier

0

100

25000

20000

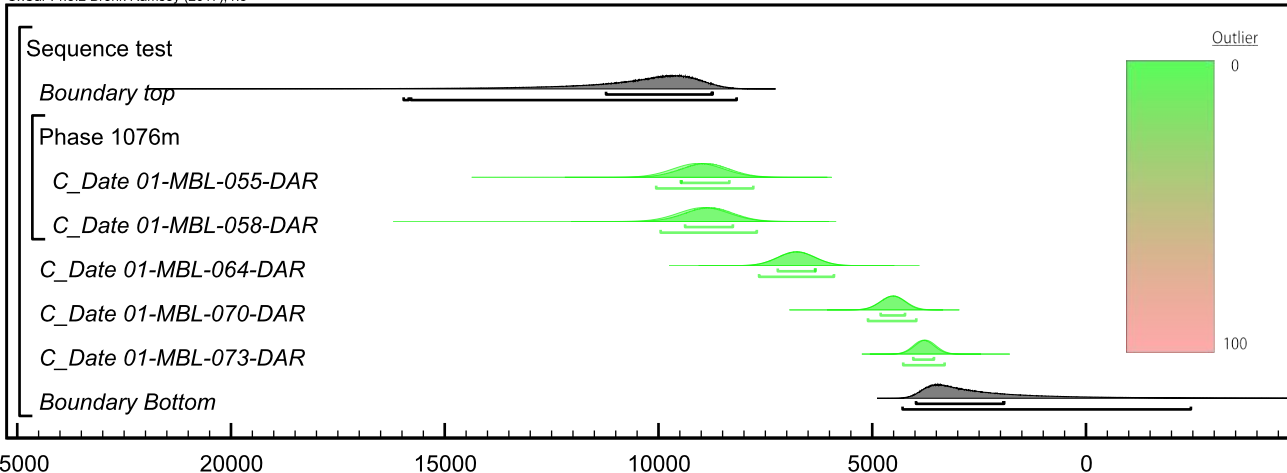
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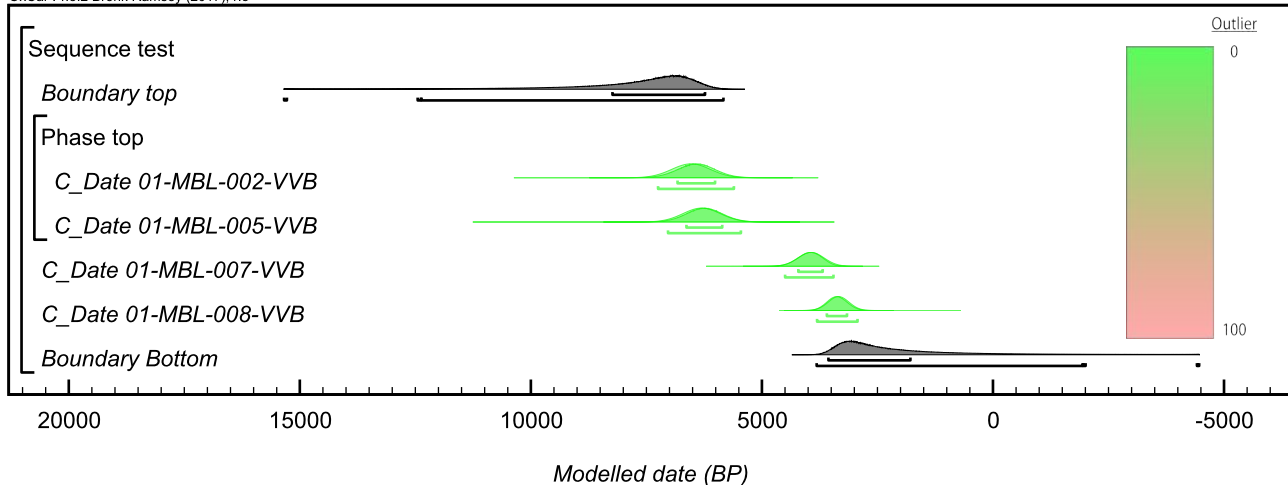
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Modelled date (BP)



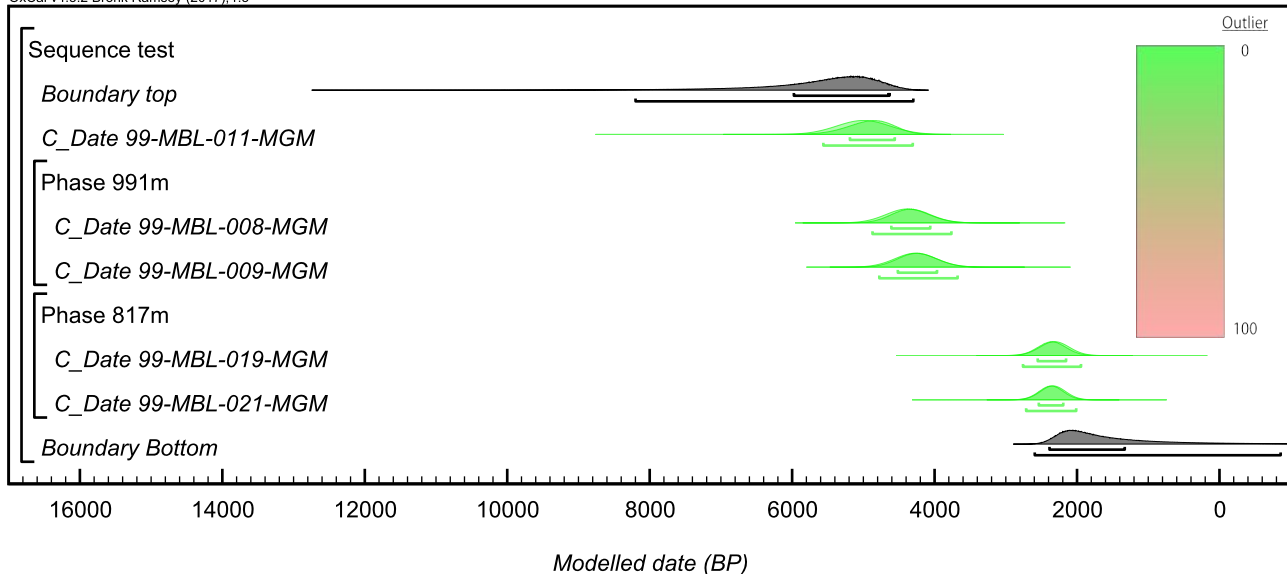
Mt Valkenburg

OxCal v4.3.2 Bronk Ramsey (2017); r:5



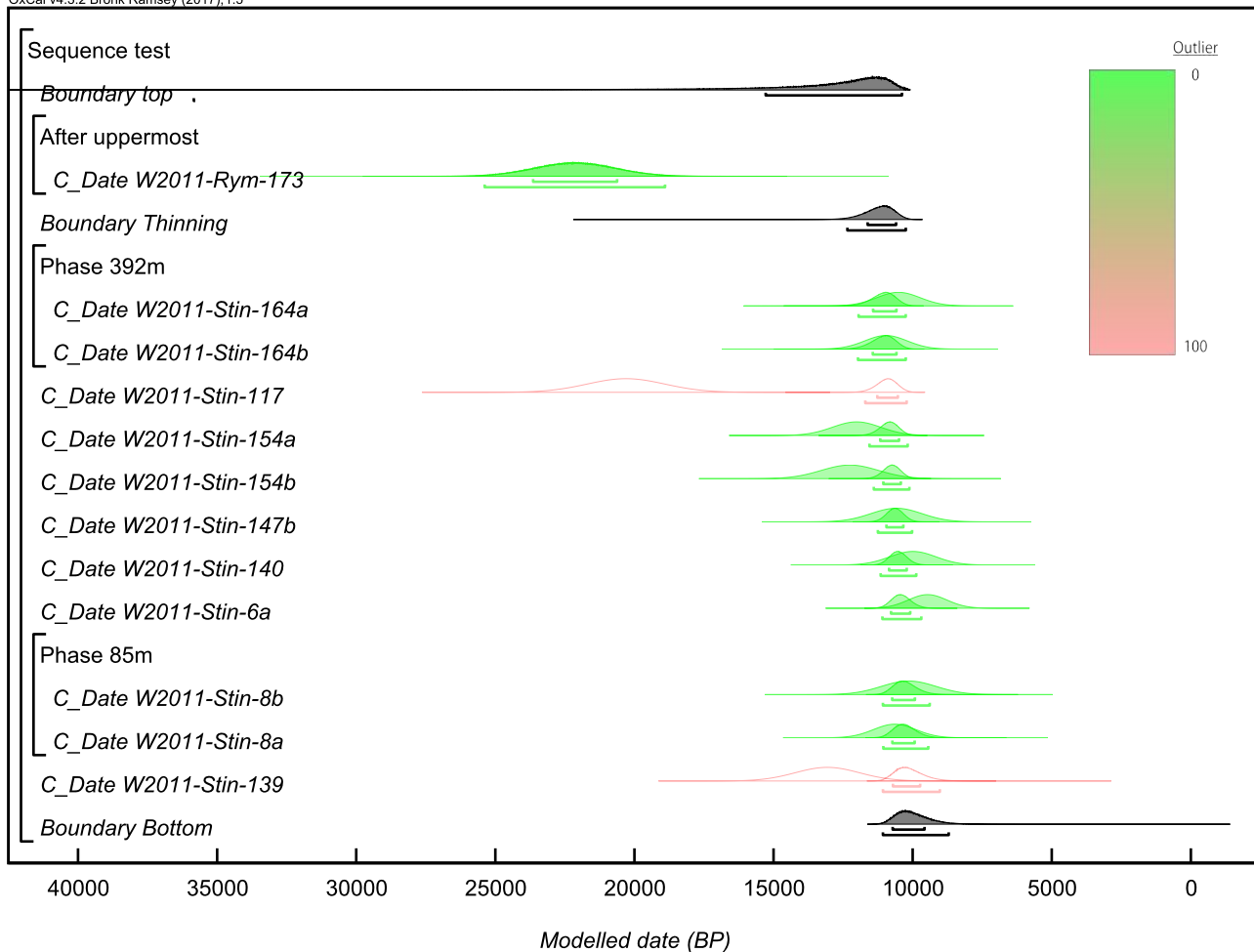
Fosdick Mountains

OxCal v4.3.2 Bronk Ramsey (2017); r:5



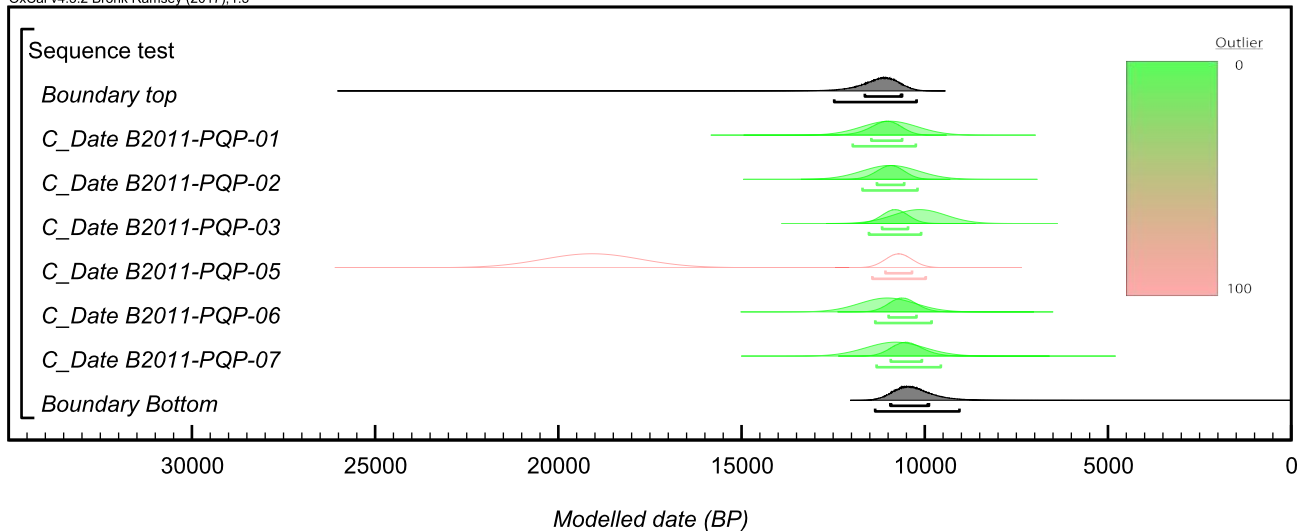
Mt Stinear

OxCal v4.3.2 Bronk Ramsey (2017); r:5



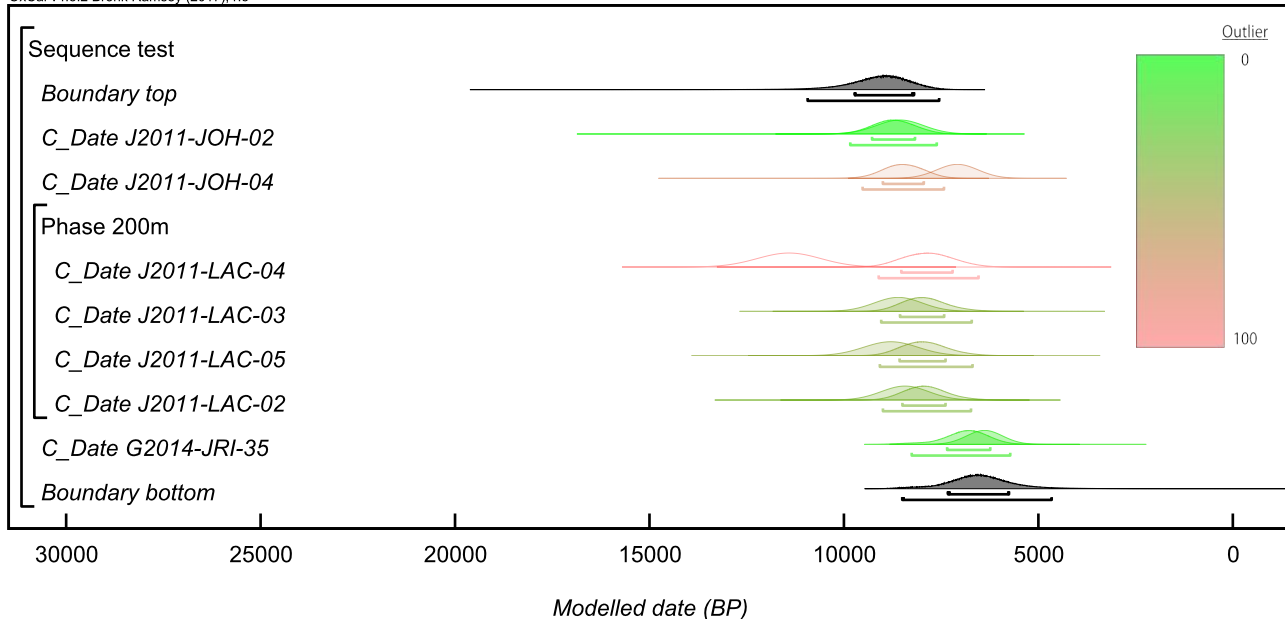
Pourquoi-Pas Island

OxCal v4.3.2 Bronk Ramsey (2017); r:5



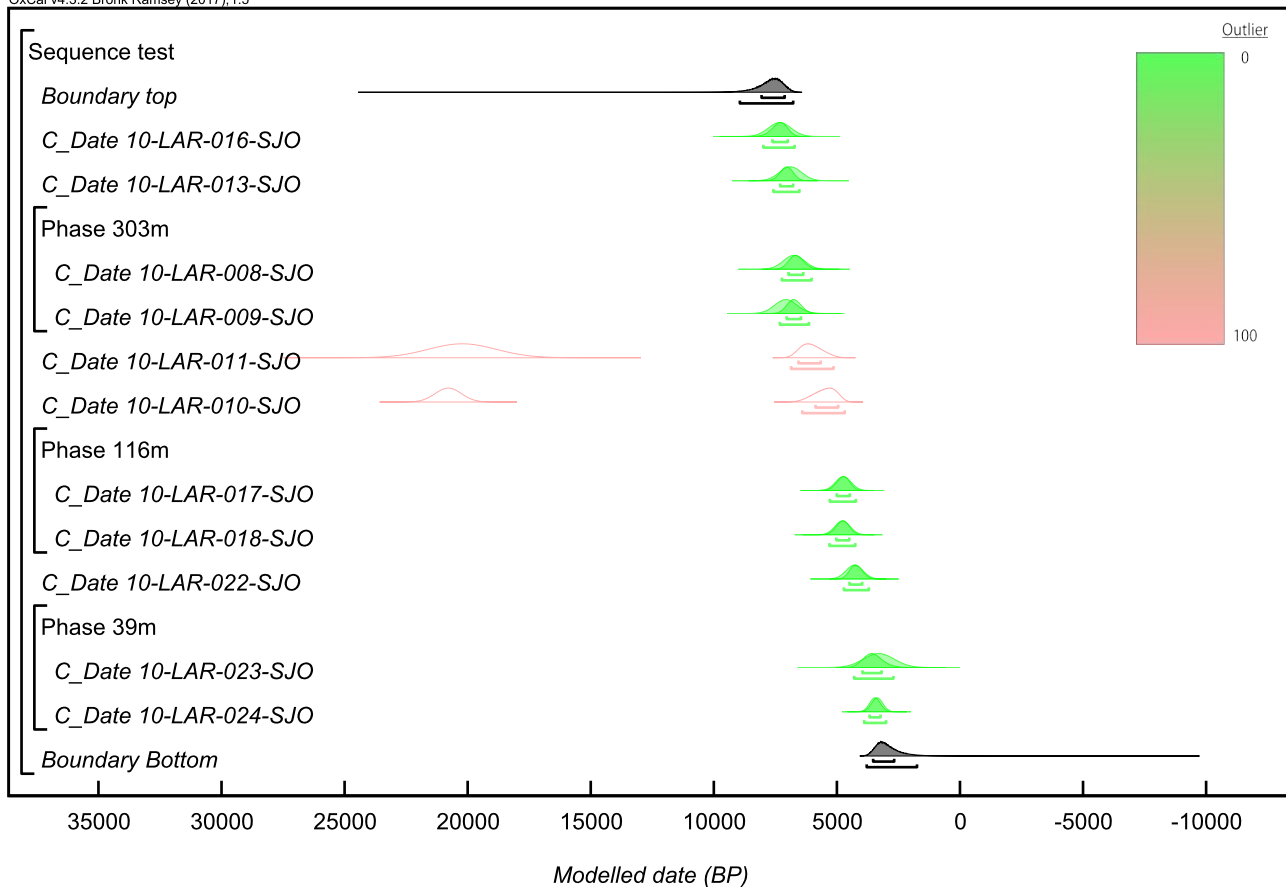
James Ross Island (Cape Lachmann)

OxCal v4.3.2 Bronk Ramsey (2017); r:5



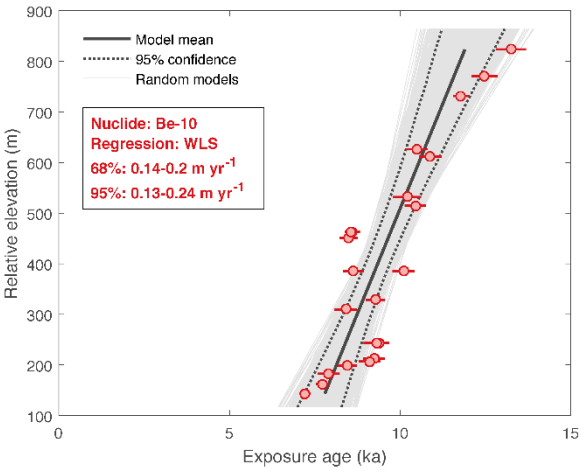
Sjorden-Boydell

OxCal v4.3.2 Bronk Ramsey (2017); r:5

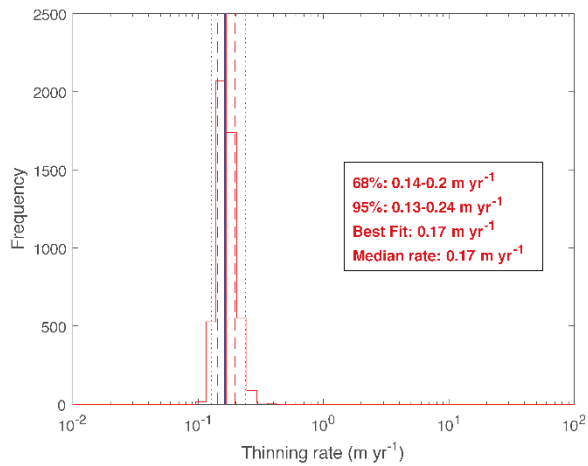


Site 1 – Mount Hope: A) Regressions, B) Histogram.

A)

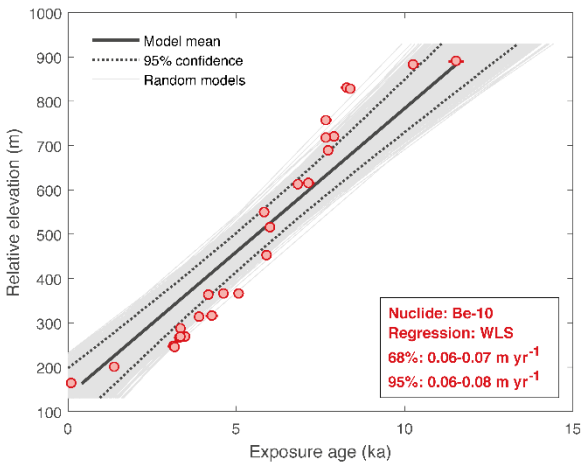


B)

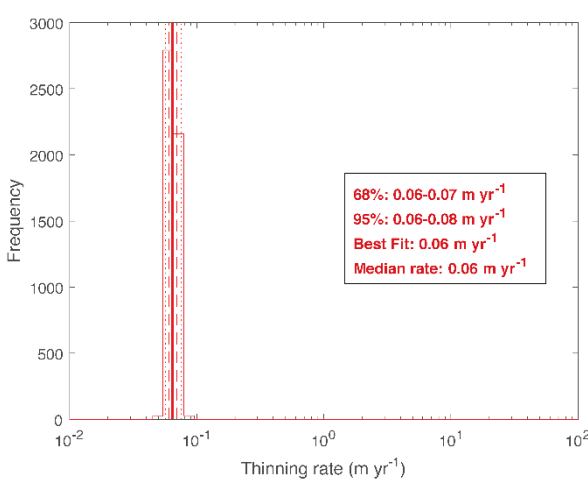


Site 2 – Mount Rigby/Karo

A)

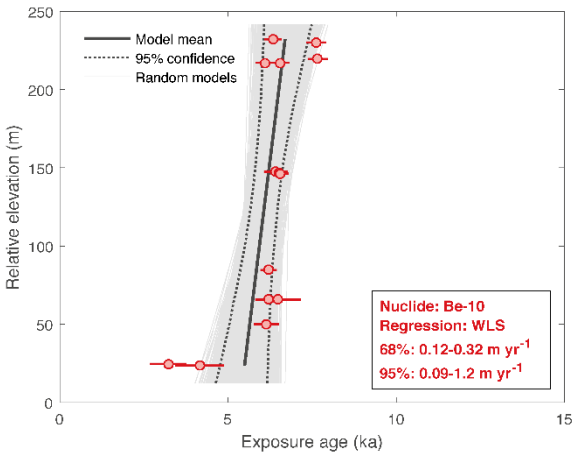


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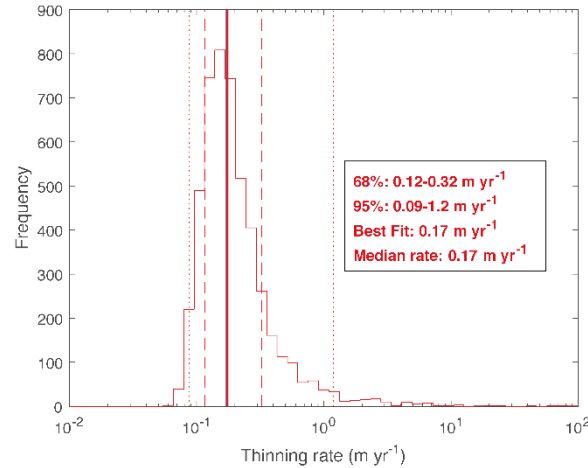


Site 3 – Mount Sues - Gondola Upper

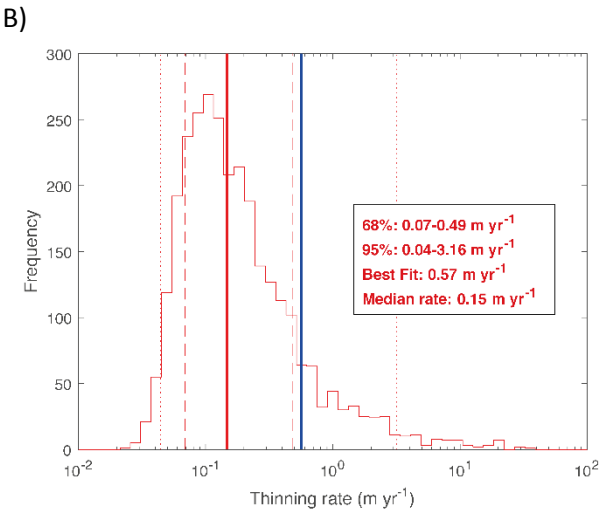
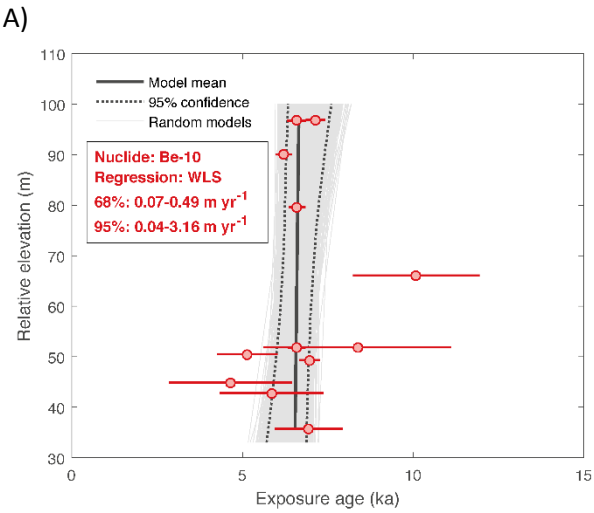
A)



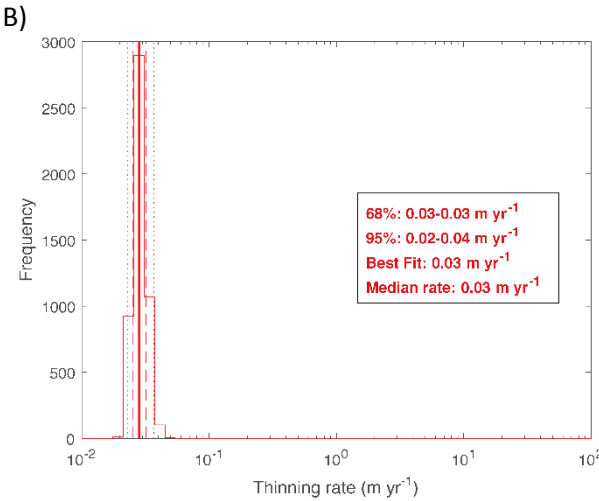
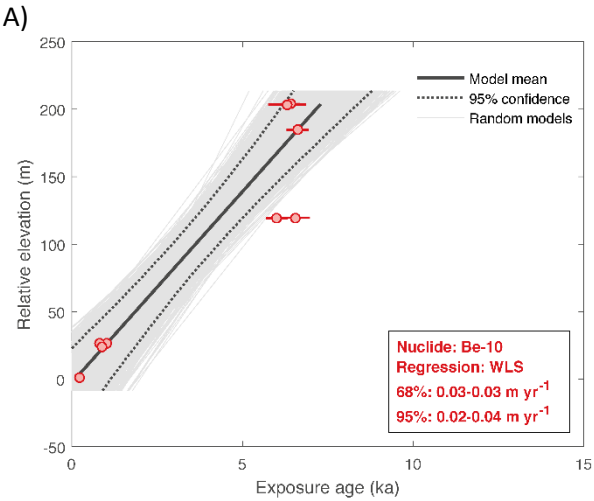
B)



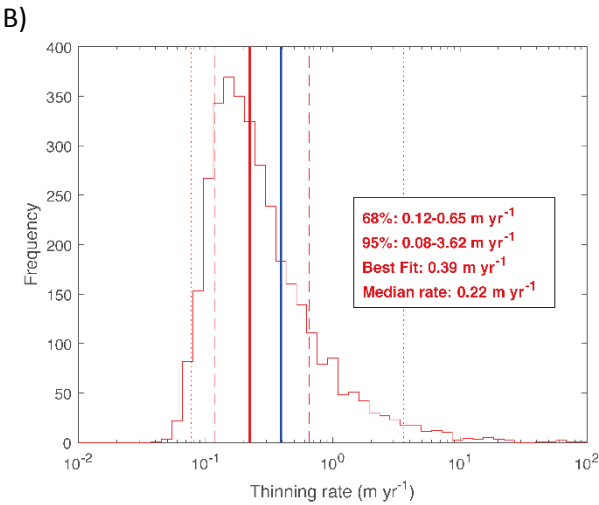
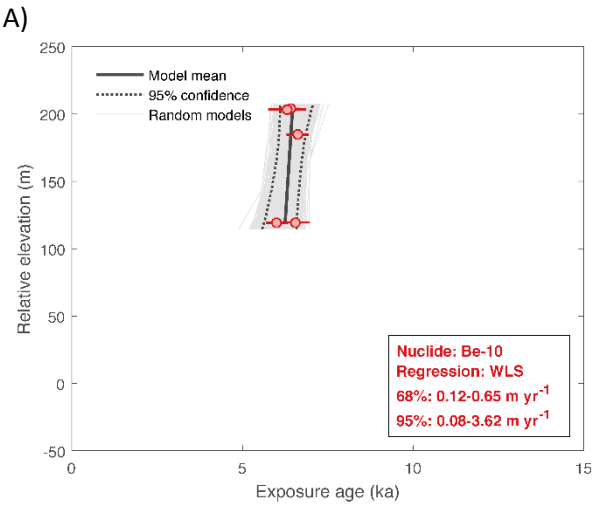
Site 4 – Gondola Mid-Lower



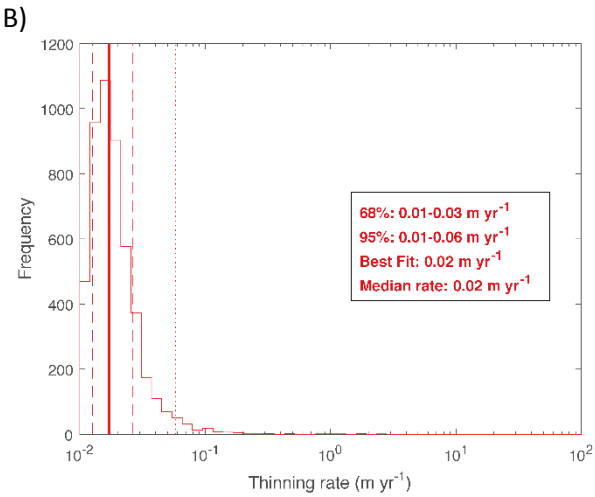
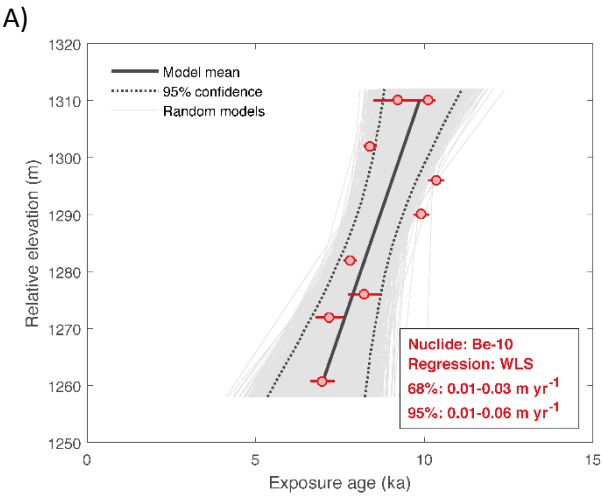
Site 5 – Low Ridge (all samples)



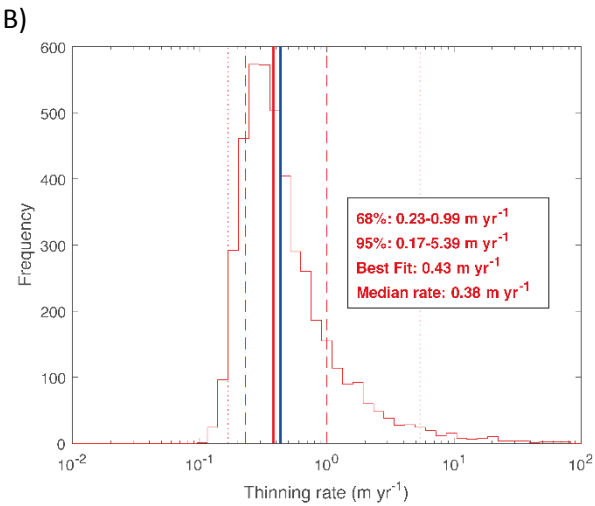
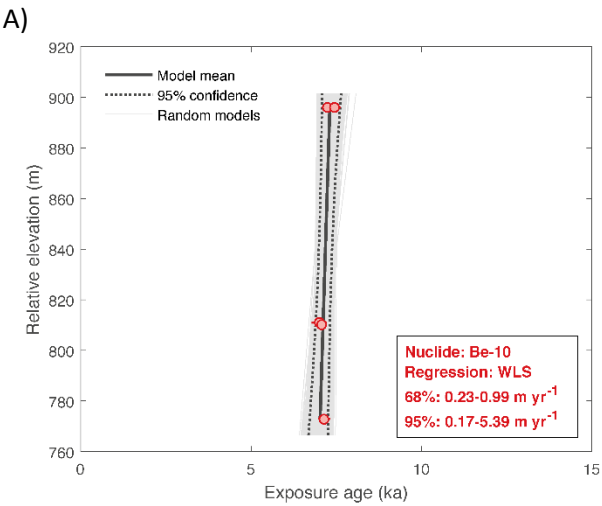
Site 5a – Low Ridge (subset n=5)



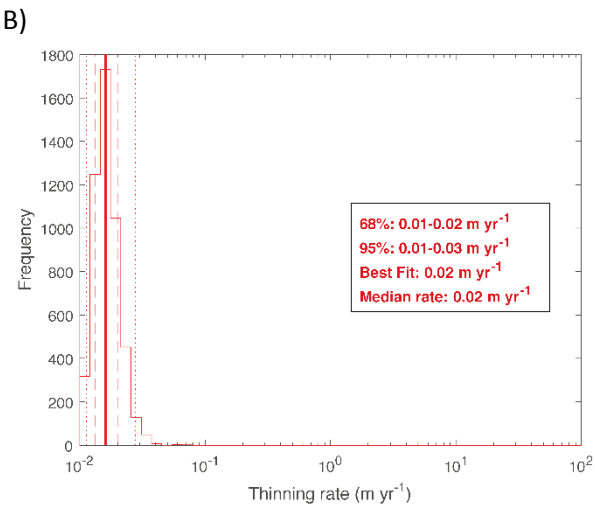
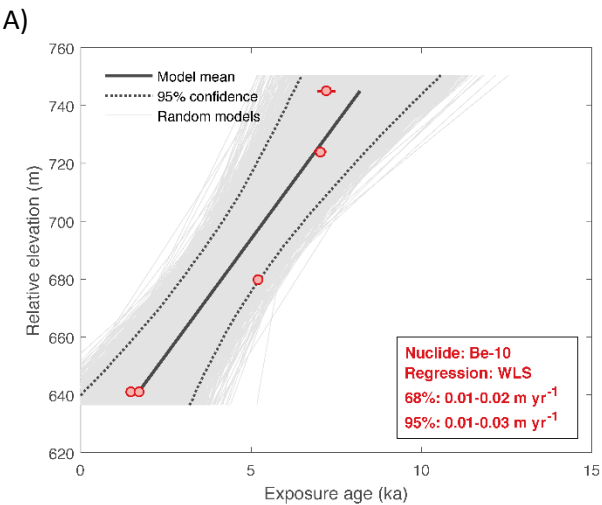
Site 6 – Reedy Glacier (Quartz Hills)



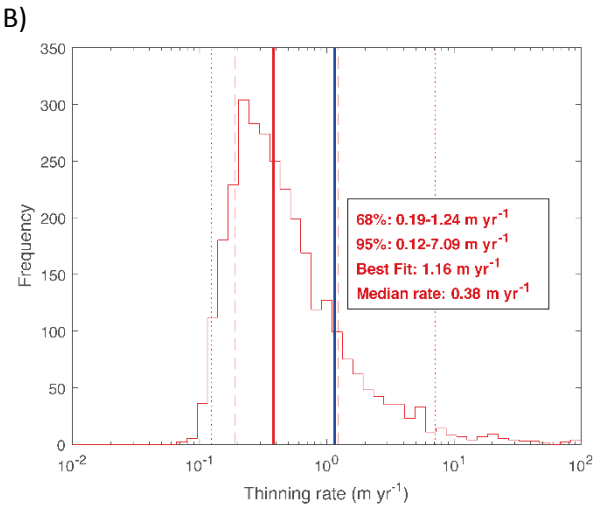
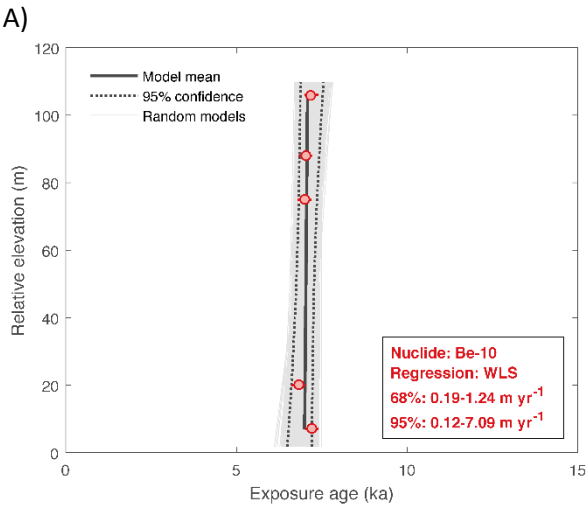
Site 7 – Reedy Glacier (Pip’s Peak)



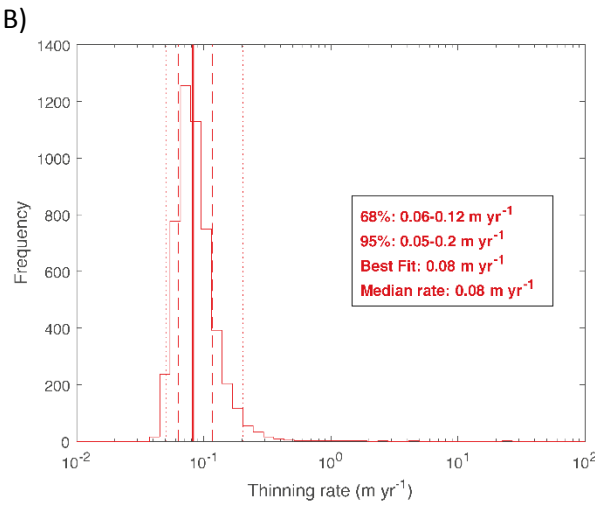
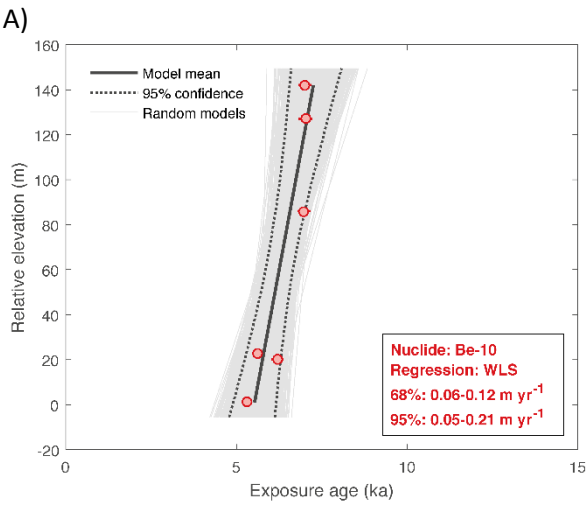
Site 8 – Reedy Glacier (Cohen’s Peak)



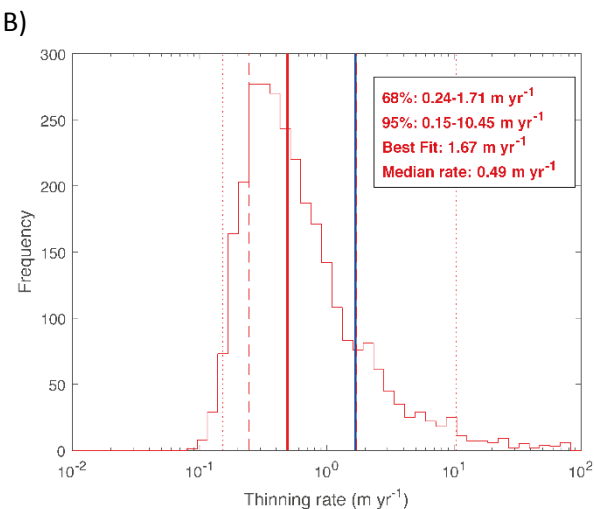
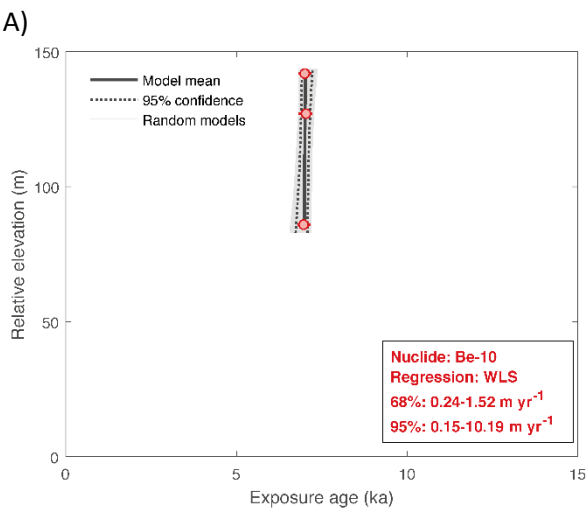
Site 9 – Mount Maish



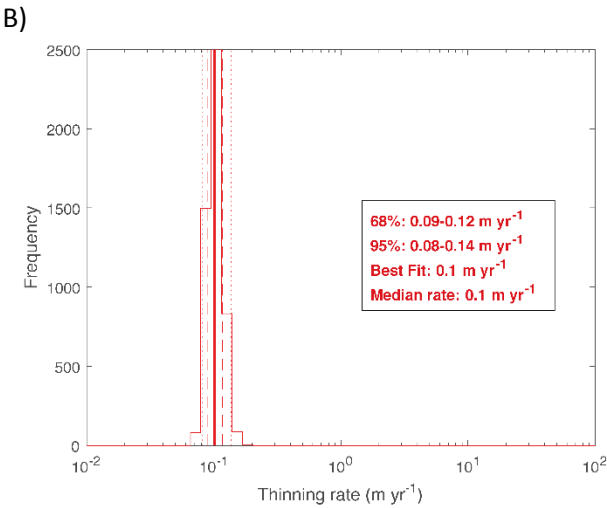
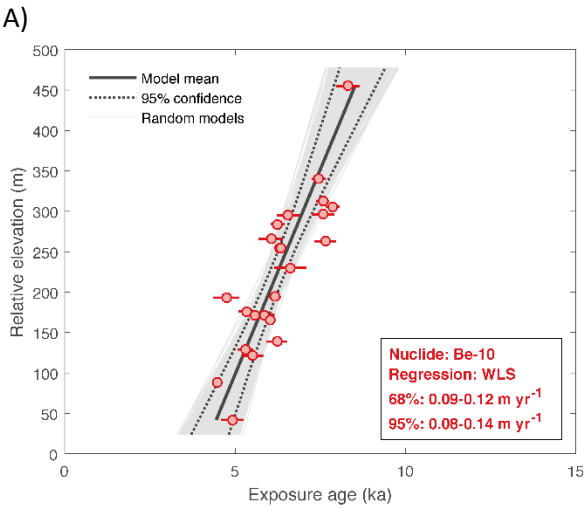
Site 10 – Mount Moses (all samples)



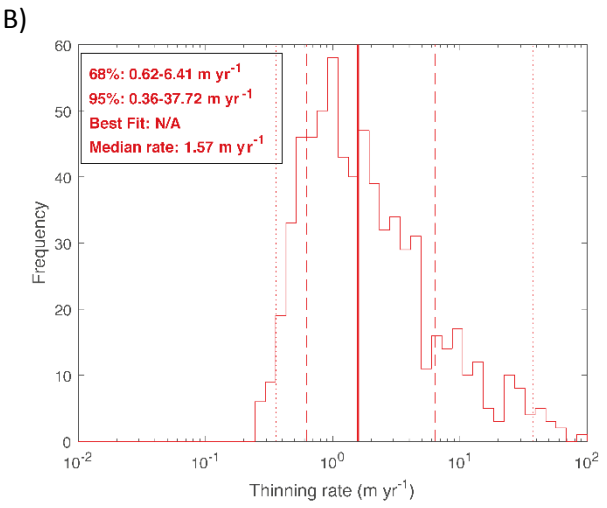
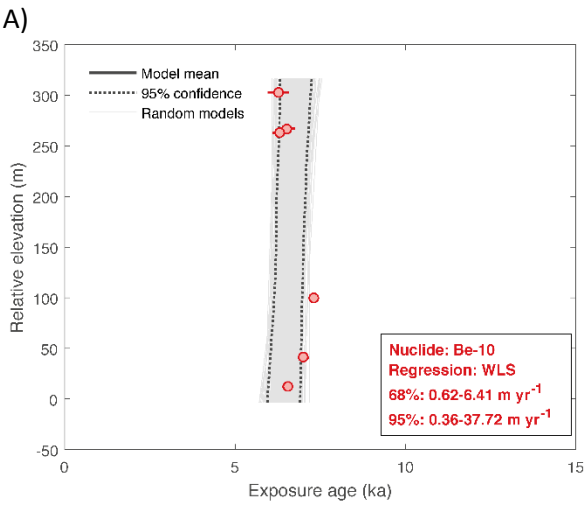
Site 10a – Mount Moses (subset n=3)



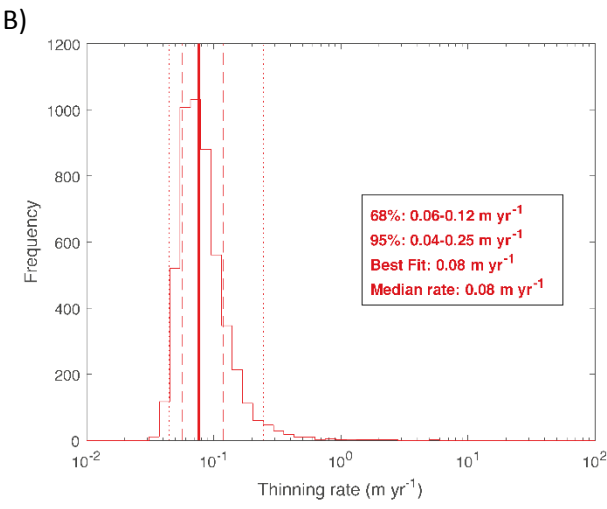
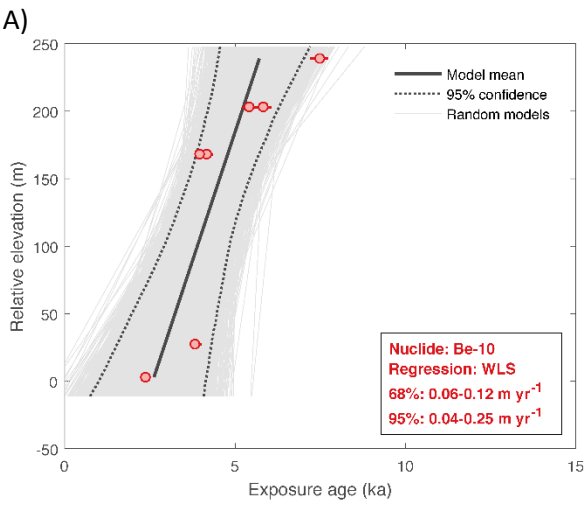
Site 11 – Williams Hills



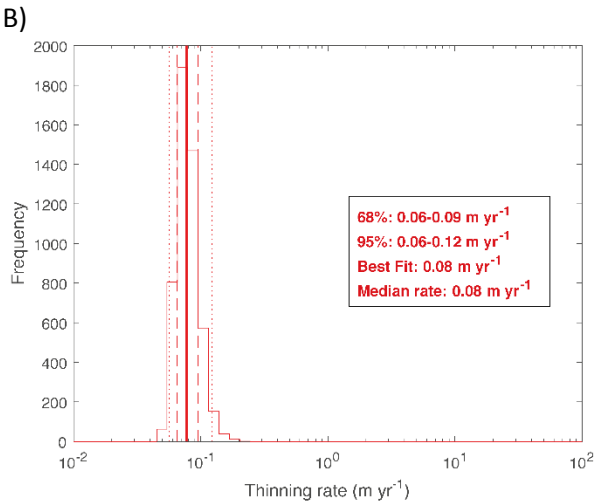
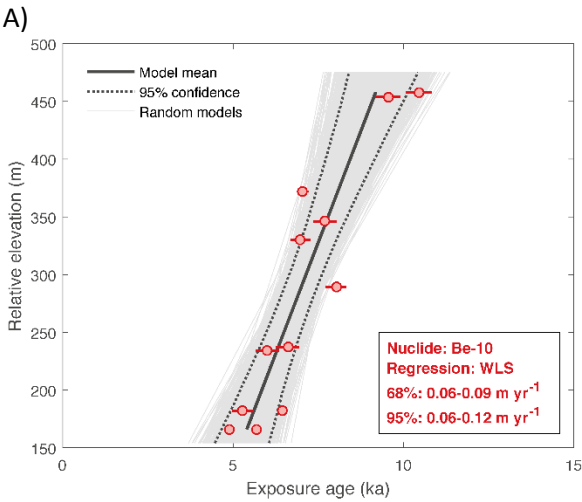
Site 12 – Thomas Hills



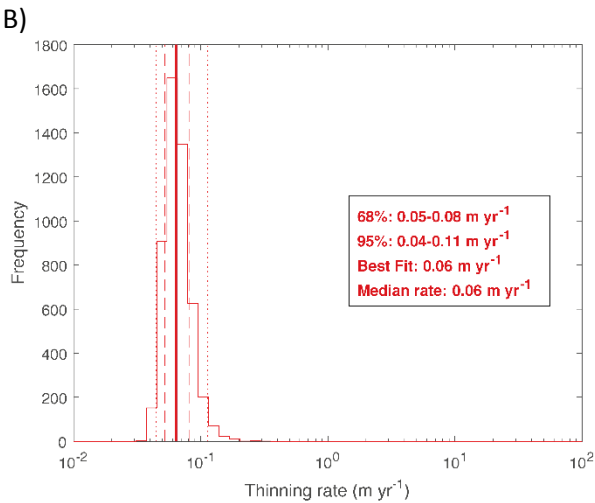
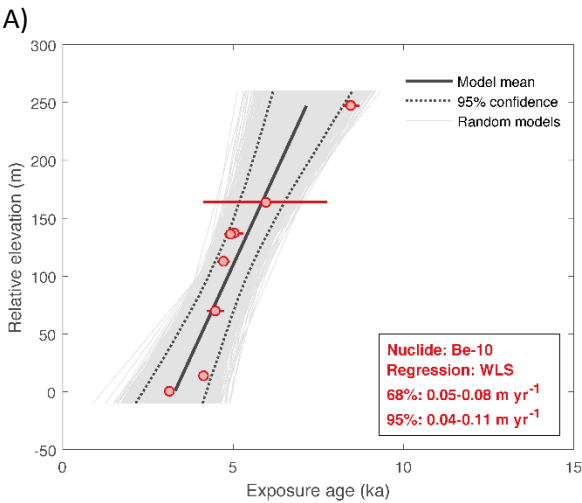
Site 13 – Mount Harper/Bragg



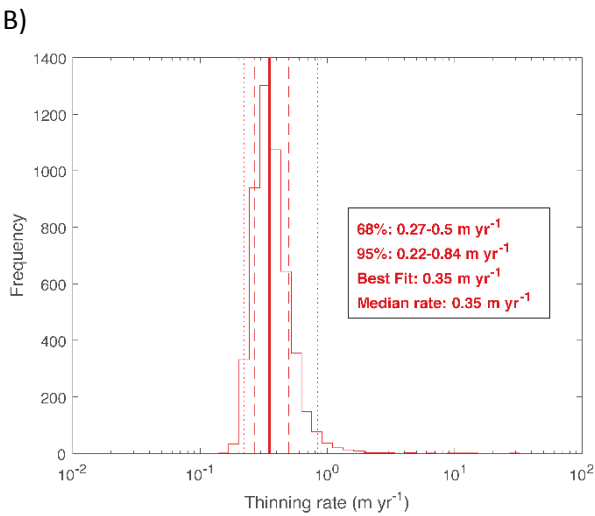
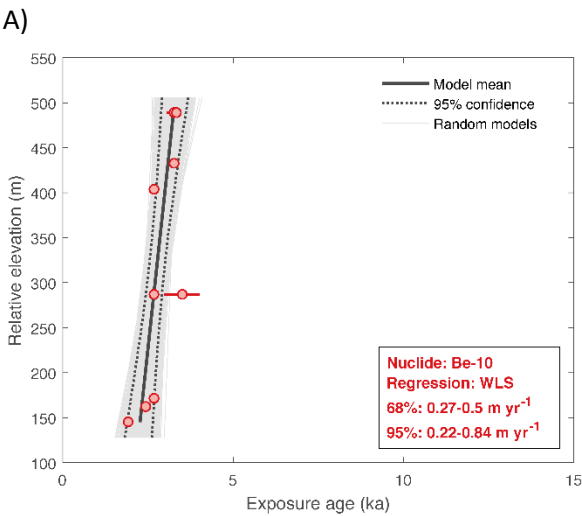
Site 14 – Marble Hills



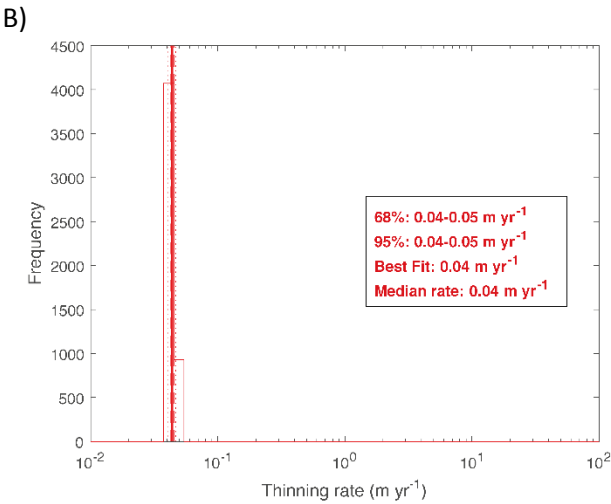
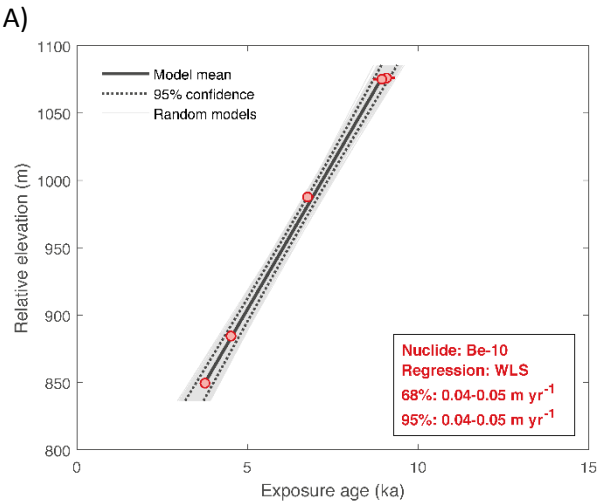
Site 15 – Patriot Hills



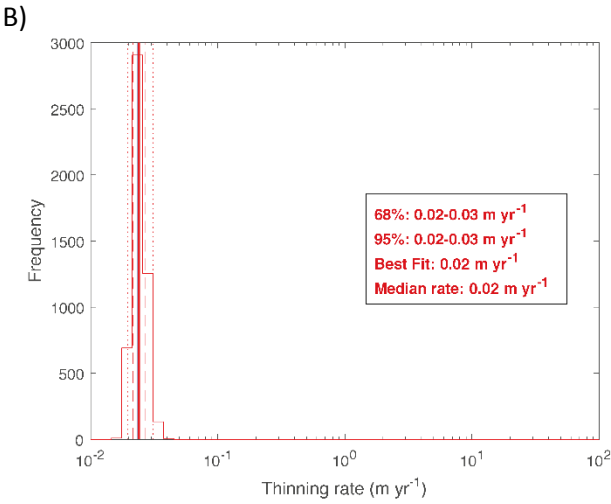
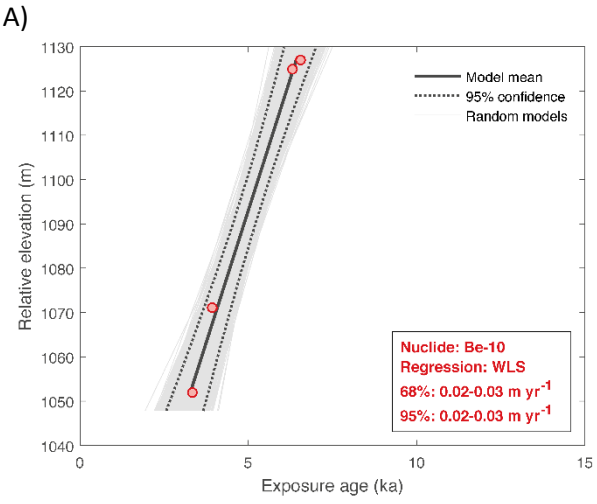
Site 16 – Mount Rea



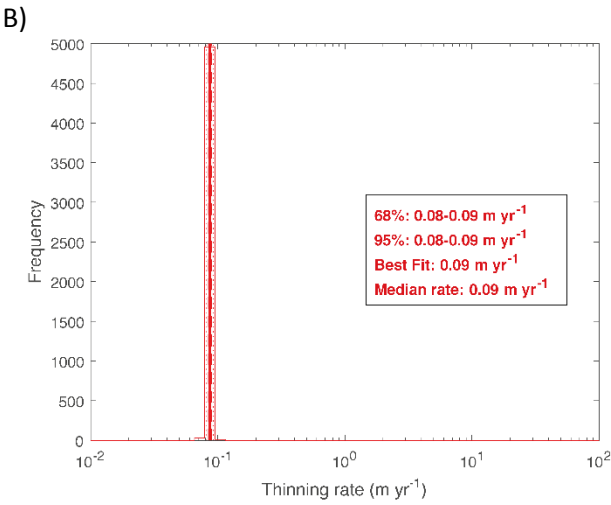
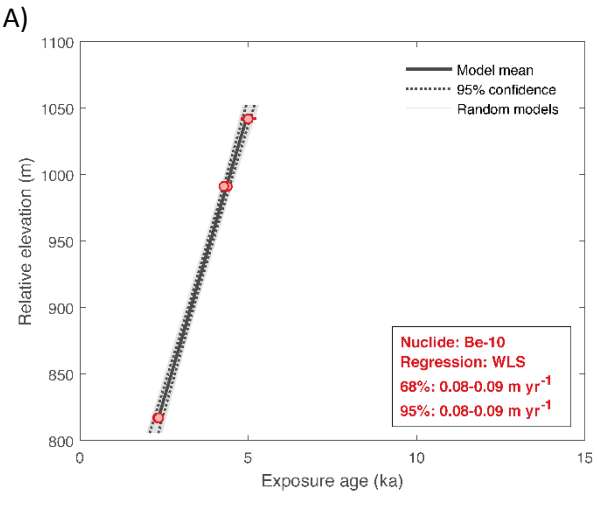
Site 17 – Mount Darling



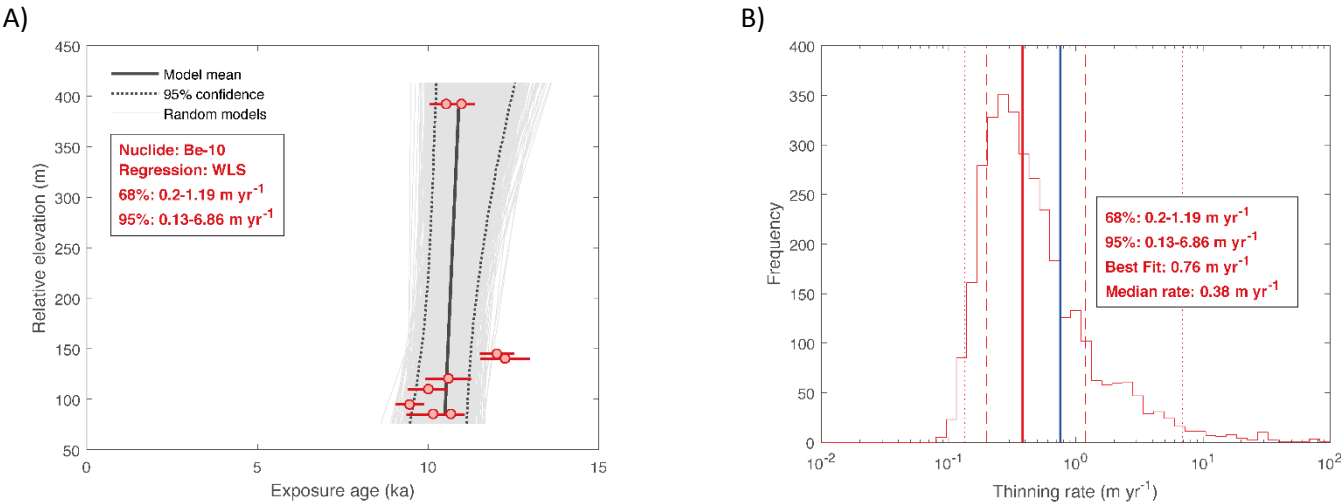
Site 18 – Mount Valkenburg



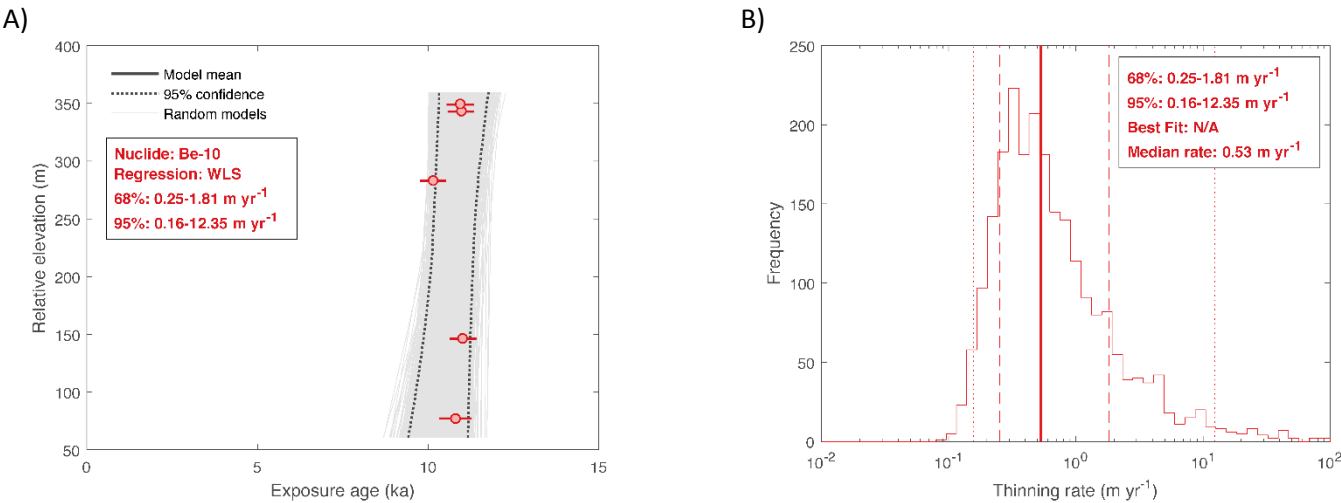
Site 19 – Fosdick Mountains



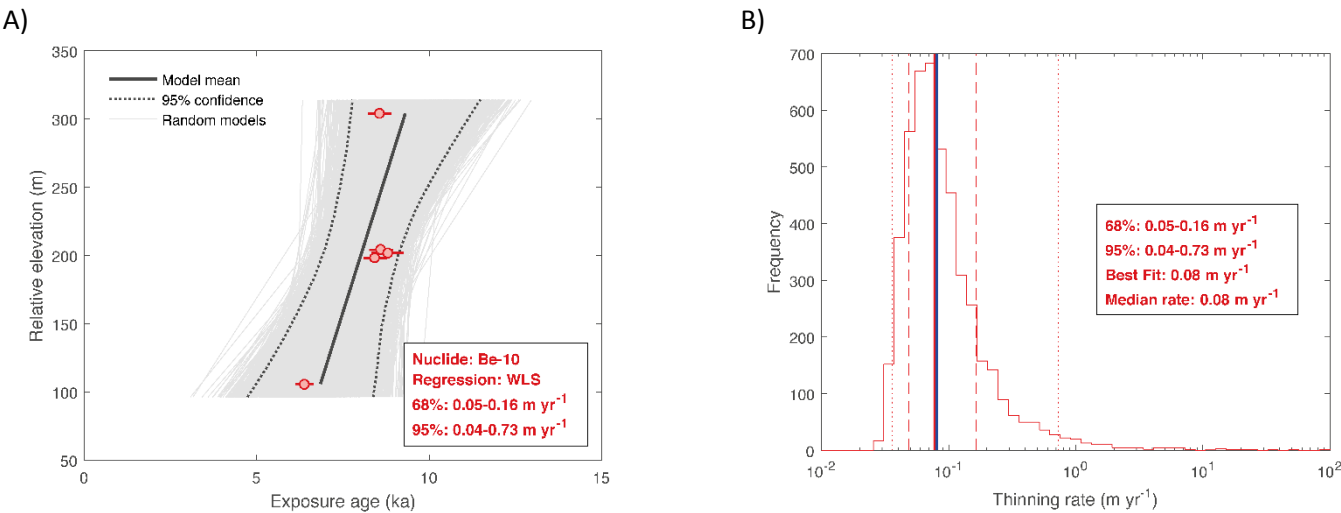
Site 20 – Mount Stinear



Site 21 – Pourquoi-Pas Island

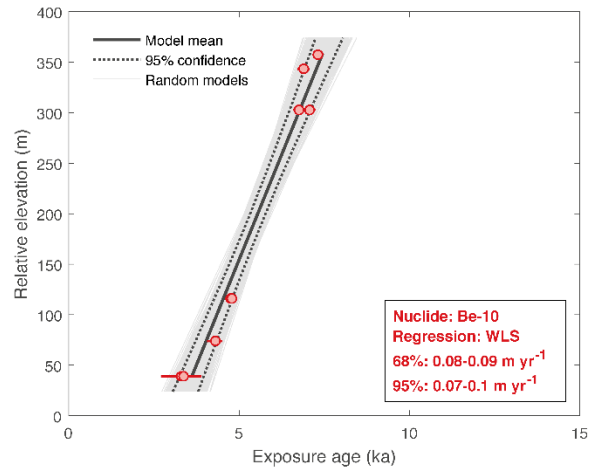


Site 22 – James Ross Island



Site 23 – Sjorden-Boydell Fjord

A)



B)

